Bulk Properties and Collective Dynamics

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Many thanks to the conference organizers

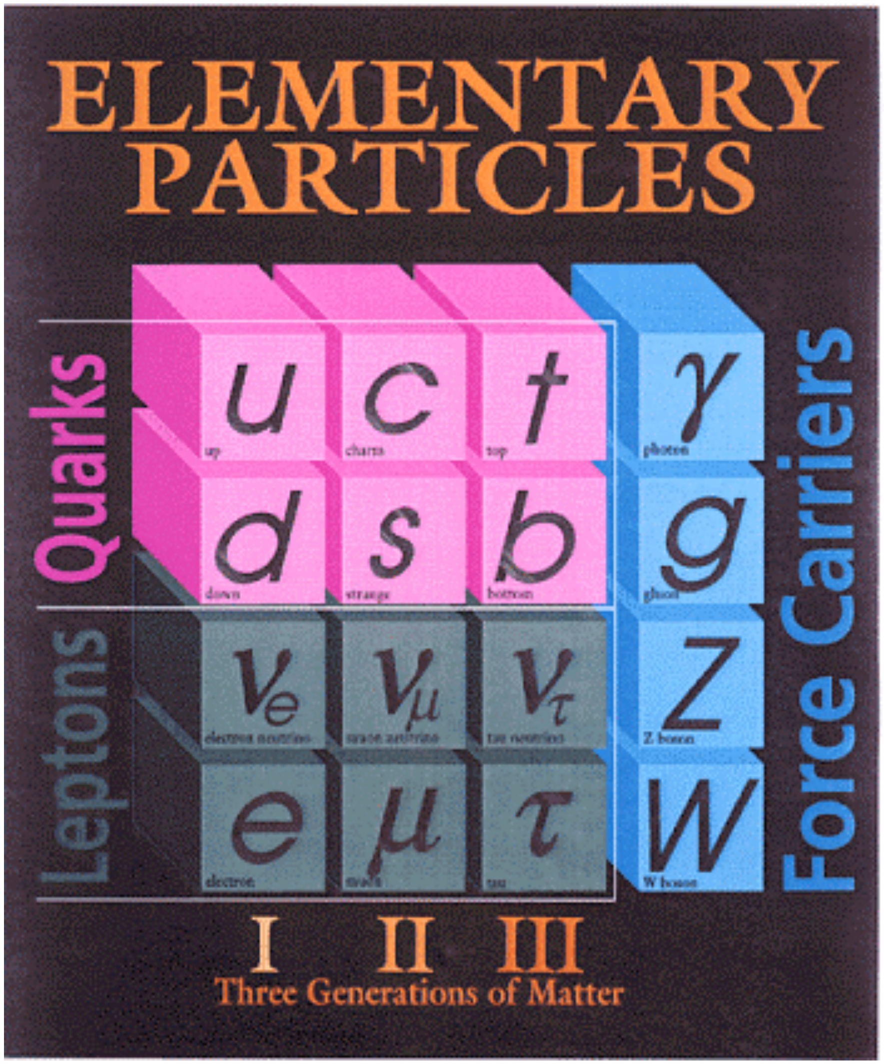
Outline

1) Introduction
   - Hydrodynamic approach
   - Collectivity, local thermalization

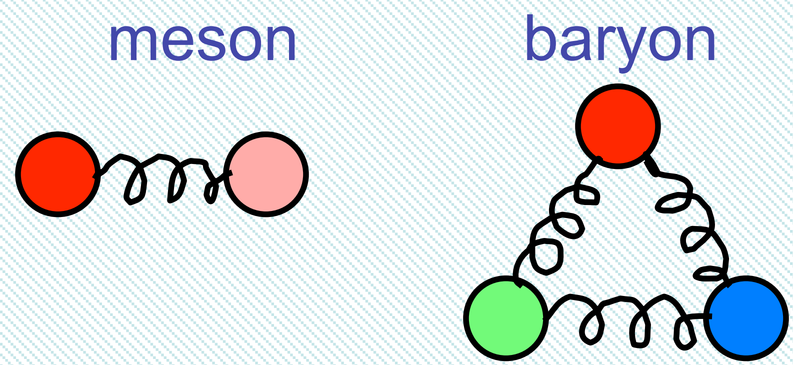
2) Recent experimental data
   - Transverse momentum distributions
   - Partonic collectivity at RHIC

3) Summary and outlook

Quantum Chromodynamics



1) Quantum Chromodynamics (QCD) is the established theory of strongly interacting matter.
2) Gluons hold quarks together to from hadrons:



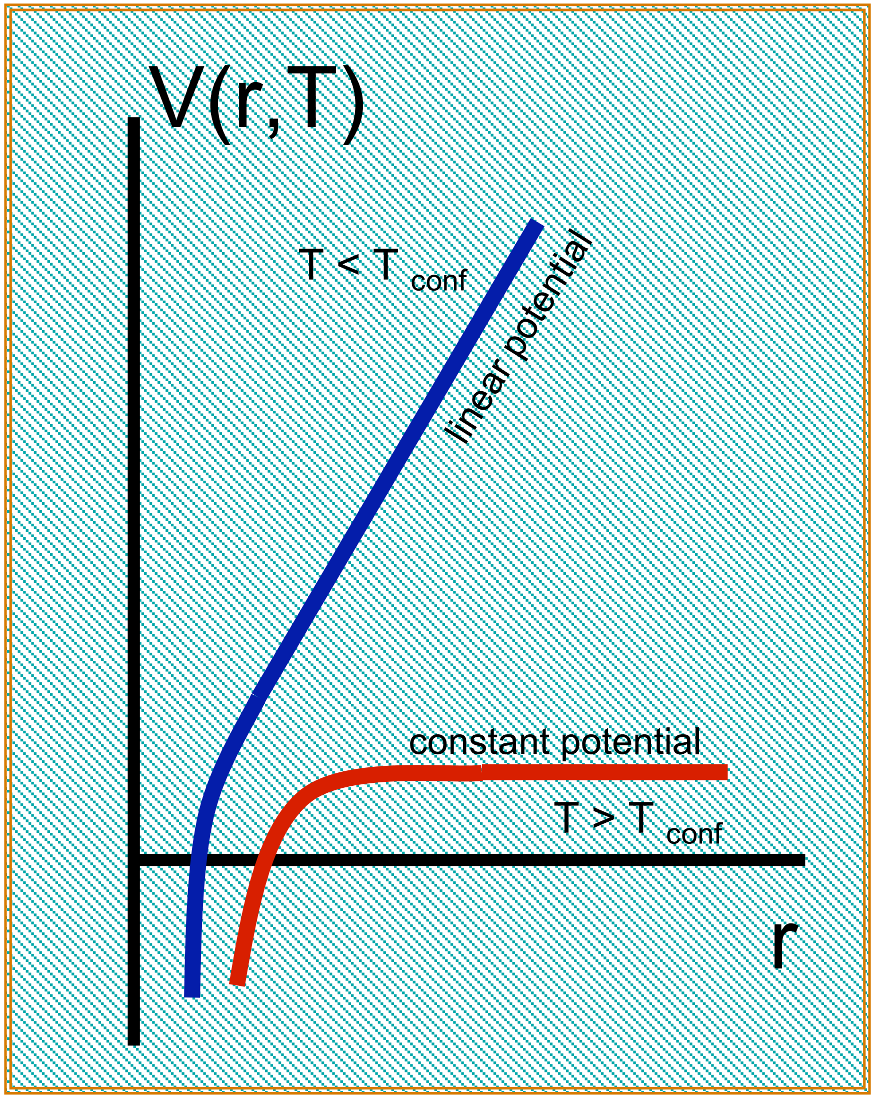
3) Gluons and quarks, or partons, typically exist in a color singlet state: confinement.

"In high-energy physics we have concentrated on experiments in which we distribute a higher and higher amount of energy into a region with smaller and smaller dimensions.

In order to study the question of **'vacuum'**, we must turn to a different direction; we should investigate some **'bulk' phenomena** by distributing high energy over a relatively large volume."

Prof. T.D. Lee, Rev. Mod. Phys. ***47***, 267(1975).

Confinement Potential



The potential between quarks is a function of distance. It also depends on
the temperature.

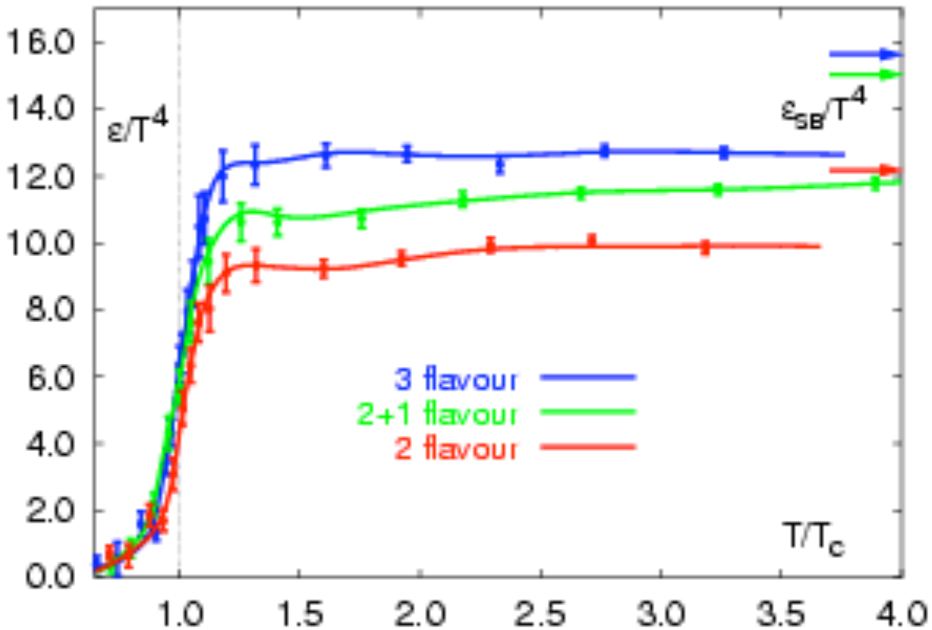
1) At low temperature, the potential increases linearly with the distance between quarks
⇒ quarks are confined;

2) At high temperature, the confinement potential is 'melted'
⇒ quarks are 'free'.

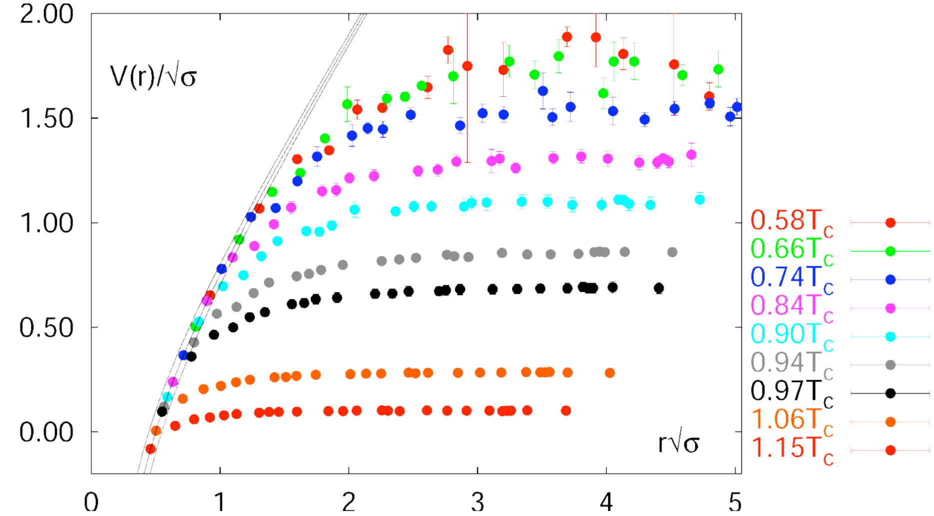
Note: It is not clear at all if there is a critical 'temperature' in high energy collisions

QCD on Predictions

Energy density



Heavy quark potential



Temperature

Left: Large increase in energy density at **T_C ~ 170 MeV**.
Not reach the non-interacting S.B. limit.

Right: Heavy quark potentials are melted at high temperature.

F. Karsch et al. Nucl. Phys. ***B524****, 123(02). Z. Fodor et al,* ***JHEP*** *0203:014(02).*
C.R. Allton et al, Nucl. Rev. ***D66****, 074507(02). F. Karsch, Nucl. Phys.* ***A698****, 199c(02).*

What Is the Problem ?

- The confinement:

Quarks are the basic building blocks of matter.

No free quarks are seen, confined within hadron:

$\Delta v_0 \sim 1\ fm^3$, $\rho_0 \sim 0.16\ fm^{-3}$, $\varepsilon_0 \sim 0.15\ GeV/fm^3$

- Heavy ion collisions: Large, hot, and dense system

$\Delta v \sim 1000\ fm^3 = 1000\ v_0$

$\rho \gg 3\ fm^{-3} \sim 20\ \rho_0$ $\Rightarrow$ QGP(?)

$\varepsilon \gg 3\ GeV/fm^3 \sim 20\ \varepsilon_0$

Quarks and gluons are 'freely' moving in a large volume

New form of ***matter with partonic degrees of freedom***

- Connection with other fields

cosmology, origin of the universe, evolution of the universe

quantum statistics with partons

Statistical QCD and dof

$$\varepsilon_{QED} = \frac{\pi^2}{30}\left[\underbrace{2}_{\text{photon spin}} + \frac{7}{8}\underbrace{2\times 2}_{\text{electron spin}}\right]T^4$$

$$\varepsilon_{QCD} = \frac{\pi^2}{30}\left[\underbrace{2\times 8}_{\text{gluon spin, color}} + \frac{7}{8}\underbrace{2\times 2\times 3\times 3}_{\text{quark spin, color, flavor}}\right]T^4$$

Energy density reflects on what the matter is made of !

Hadron ⇔ Quark-gluon Gas

1) Facts:
   - hadron radius $r_h \sim 1$ fm
   - $T \geq T_c \sim 1/r_h = 0.2$ GeV

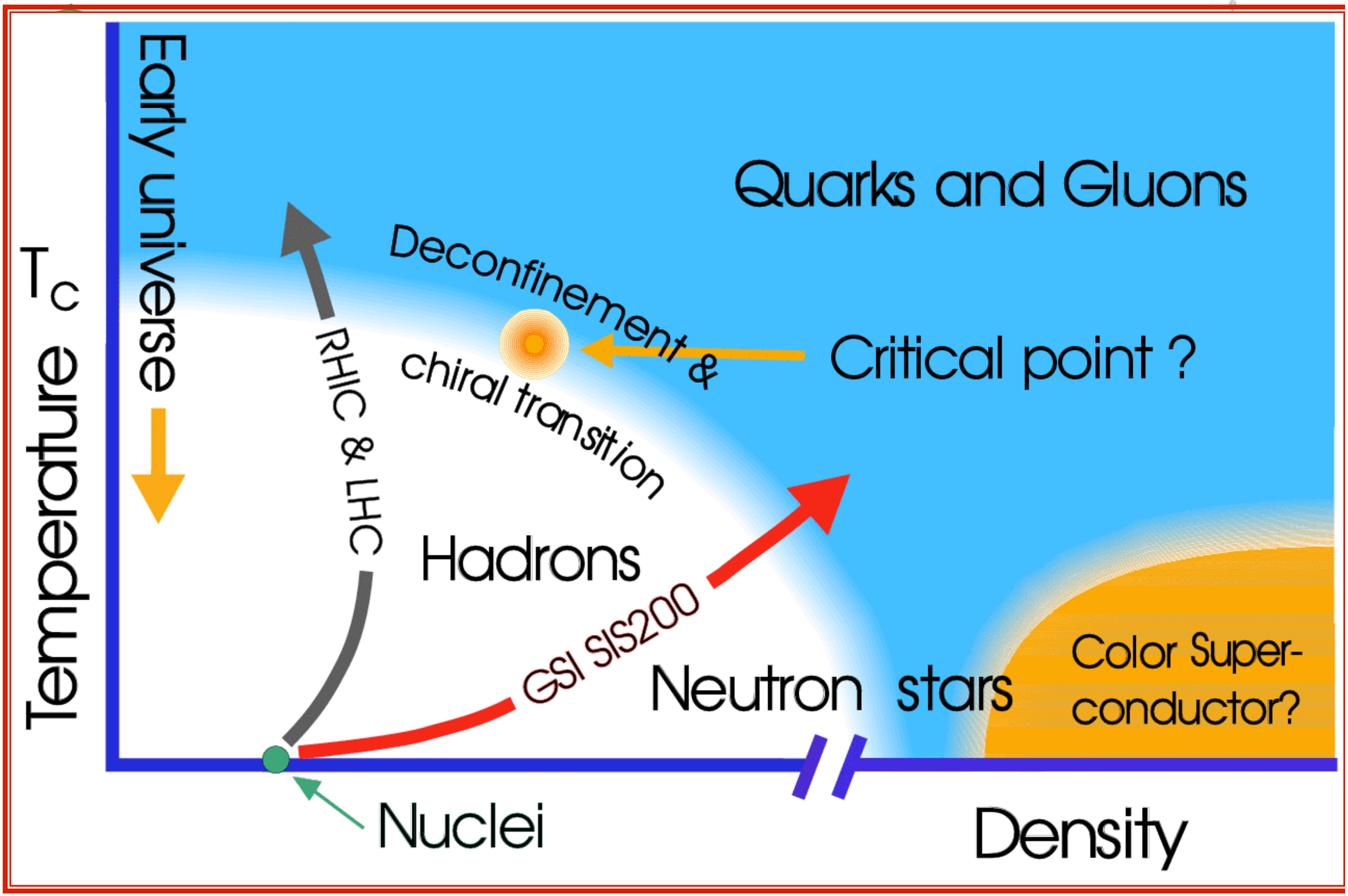
2) Hadron to parton transition
   $T \geq T_c$ GC partition function becomes divergent

*I.Ya Pomeranchuk, Dokl.Akas.Nauk SSSR **78**, 889(1951)*
*R. Hagedorn, Nuovo Cim.Suppl. **3**, 147(1965)*

$$\varepsilon_\pi = \frac{\pi^2}{30} 3T^4 \propto T^4$$

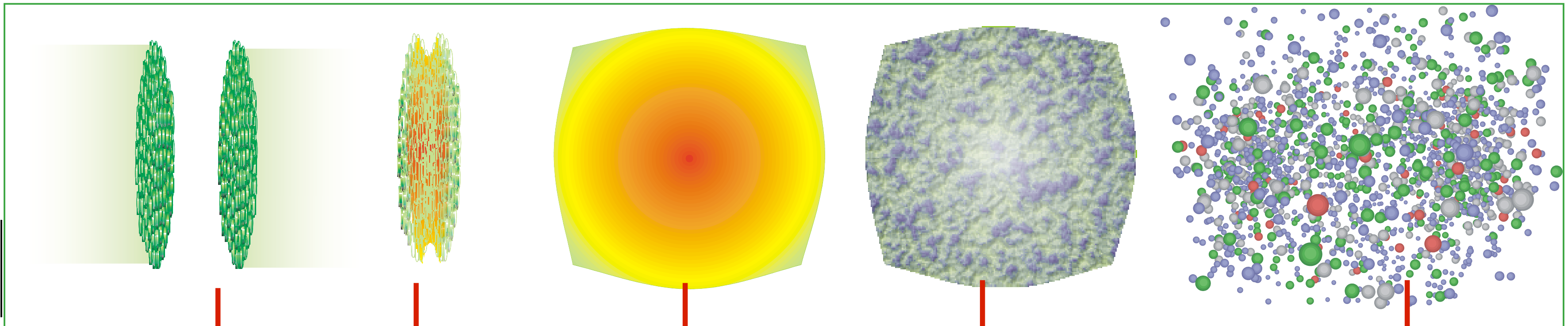
$$\varepsilon_{QCD} \propto 16T^4$$

A large energy density increase for transition from hadron to hot quark-gluon system !


Early universe
Temperature
T_C
Quarks and Gluons
Deconfinement &
chiral transition
Critical point ?
RHIC & LHC
Hadrons
GSI SIS200
Neutron stars
Color Super-
conductor?
Nuclei
Density

High-energy Nuclear Collisions

S. Bass



Initial conditions

Initial high Q^2 interactions

Partonic matter - QGP - The hot-QCD

Hadronization and Freeze-out

(1) Hard scattering production - QCD prediction
(2) Interactions with medium - deconfinement/thermalization
(3) Initial parton density

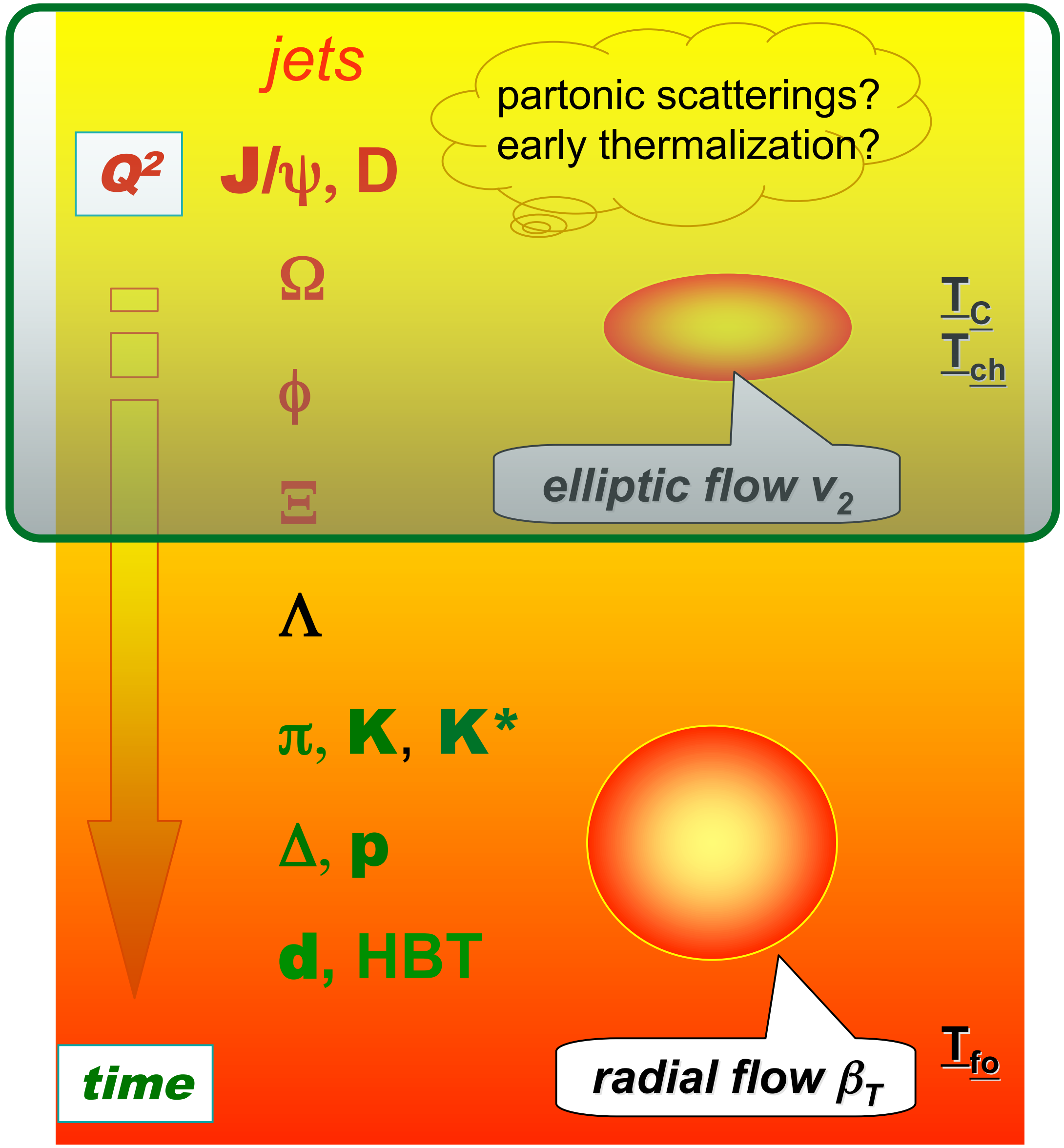
(1) Initial condition in high-energy nuclear collisions - Color Glass Condensation
(2) Cold-QCD-matter, small-x, high-parton density
- parton structures in nucleon / nucleus

High-Energy Nuclear Collisions

Initial Condition
- initial scatterings
- baryon transfer
- E_T production
- parton dof

System Evolves
- parton interaction
- parton/hadron expansion

Bulk Freeze-out
- hadron dof
- interactions stop



Physical Goals at RHIC

Identify and study the properties of matter (EoS) with partonic degrees of freedom and determine the QCD phase diagram.

Penetrating probes

- direct photons, leptons
- "jets" and heavy flavor

Bulk probes

- spectra, v_1, v_2 …
- partonic collectivity
- fluctuations

Hydrodynamic Flow = ***Collectivity*** $\otimes$ Local Thermalization

Pressure, Flow, …

$$\tau d\sigma = dU + pdV$$

σ– entropy; p – pressure; U – energy; V – volume
$\tau = k_B T$, thermal energy per dof

In high-energy nuclear collisions, *interaction* among *constituents* and *density distribution* will lead to:

pressure gradient ⇔ collective flow

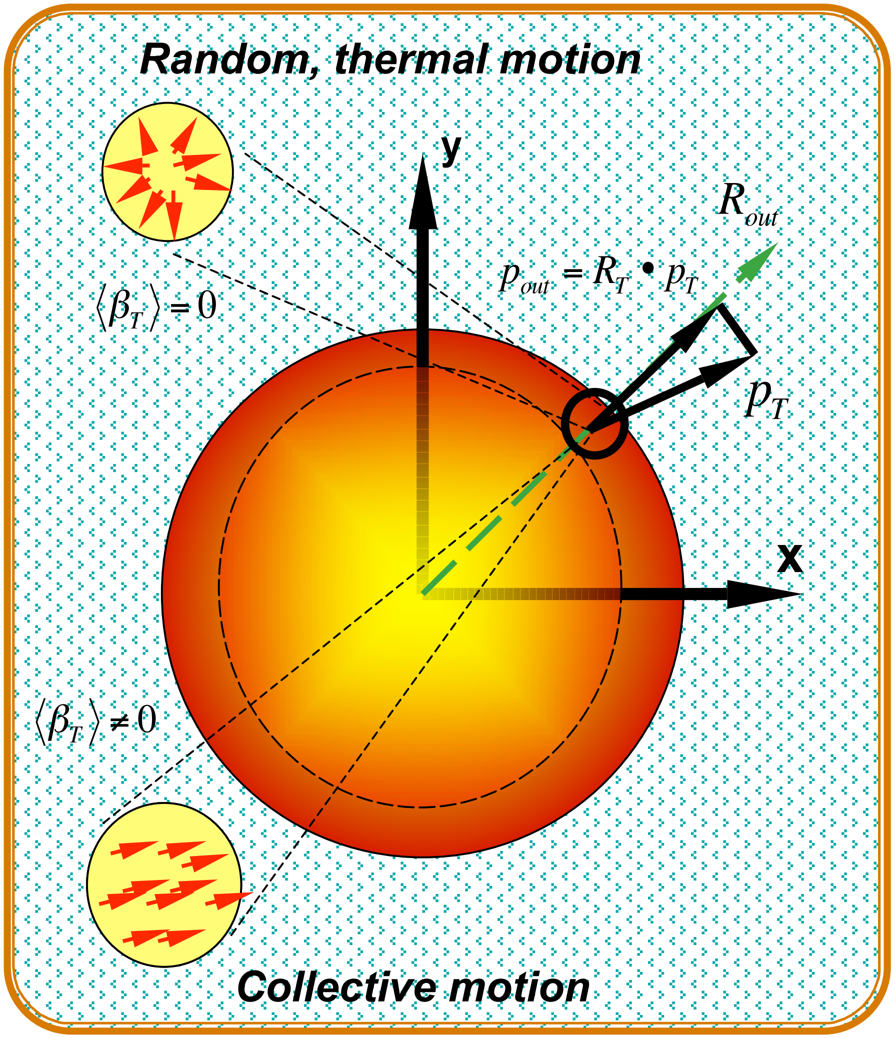
⇔ number of degrees of freedom (dof)

⇔ Equation of State (EOS)

⇔ No thermalization is needed – pressure gradient only depends on the ***density gradient and interactions***.

⇒ Space-time-momentum correlations!

Pressure, Flow, …



Matter flows – all hadrons have the similar collective velocity

Random Thermal ⊕ ***Collective***

$$\langle p_T \rangle \propto \langle p_T \rangle_{thermal} + mass * \langle v_T \rangle$$

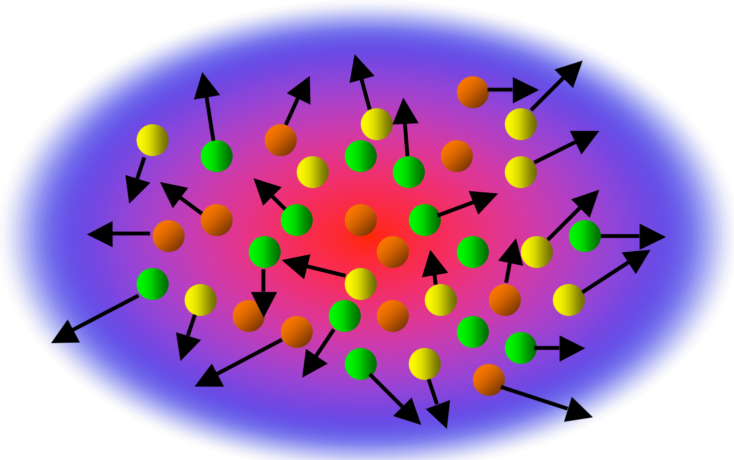
$$T \propto T_{thermal} + mass * \langle v_T \rangle^2$$

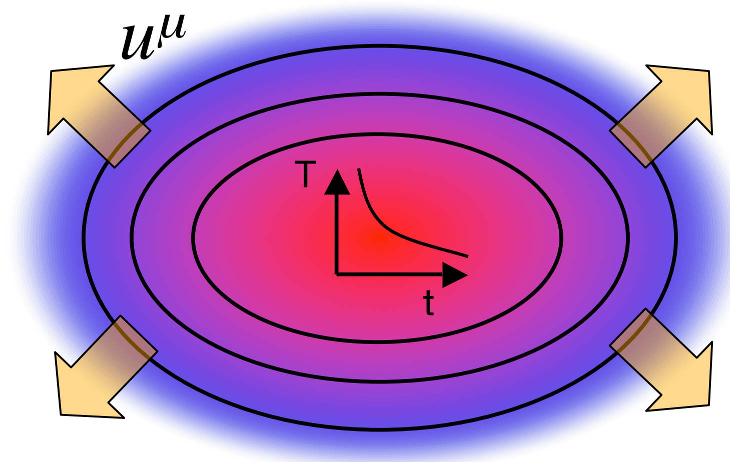
$$\langle p_T \rangle_{thermal} \propto \sqrt{mass * T_{thermal}}$$

*I.Bearden et al, Phys. Rev. Lett. **78**, 2080(97).*

Timescales of Expansion Dynamics

microscopic view vs macroscopic view





scattering rate $\nu_{ab} \sim$

$$\int \frac{d^3 p_a}{(2\pi)^3} \frac{d^3 p_b}{(2\pi)^3} f_a(p_a) f_b(p_b) \sigma_{ab}(s) \left| \vec{\mathrm{v}}_a - \vec{\mathrm{v}}_b \right|$$

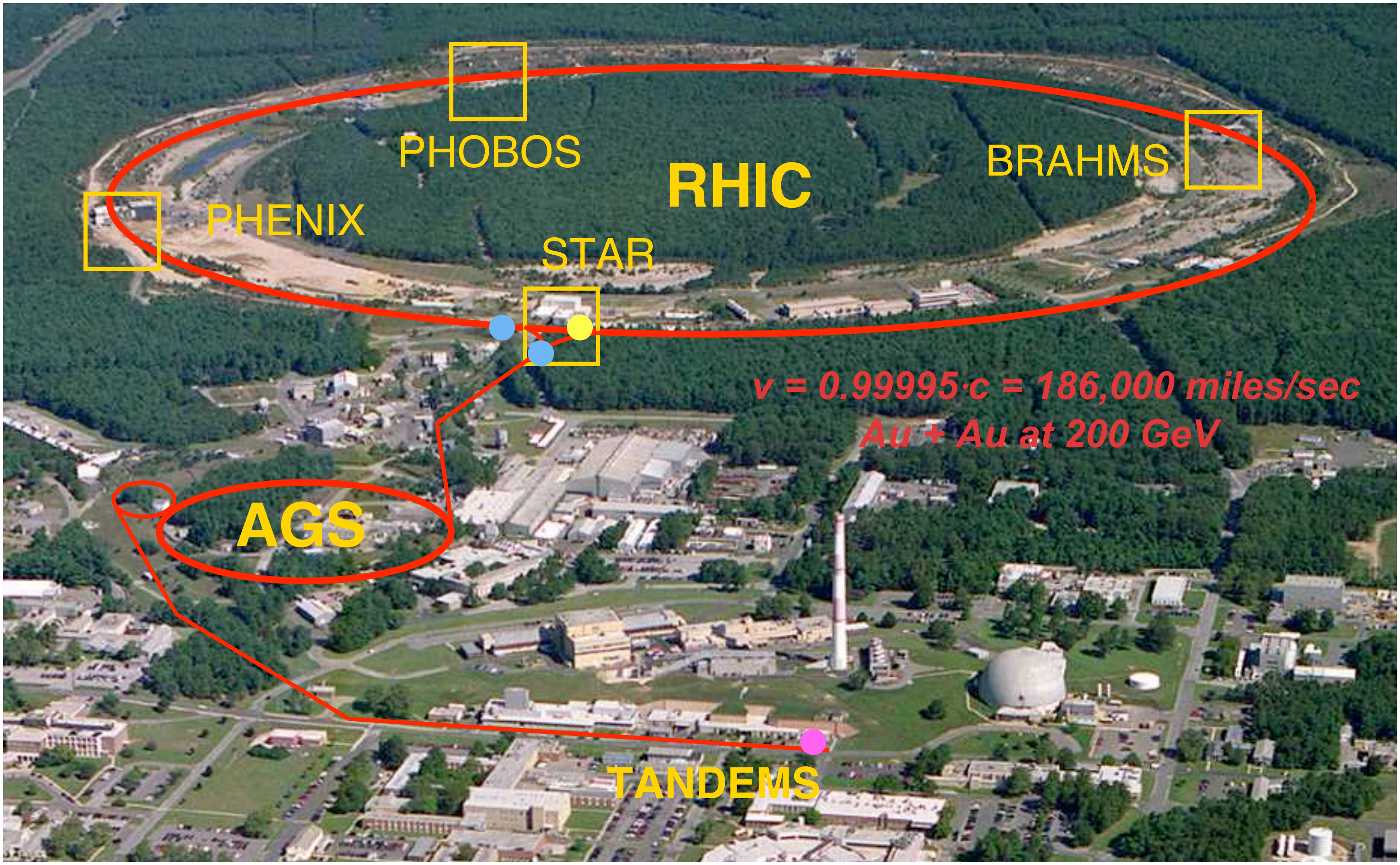
expansion rate $\partial_\mu u^\mu$

dilution rate $\partial_\tau s$

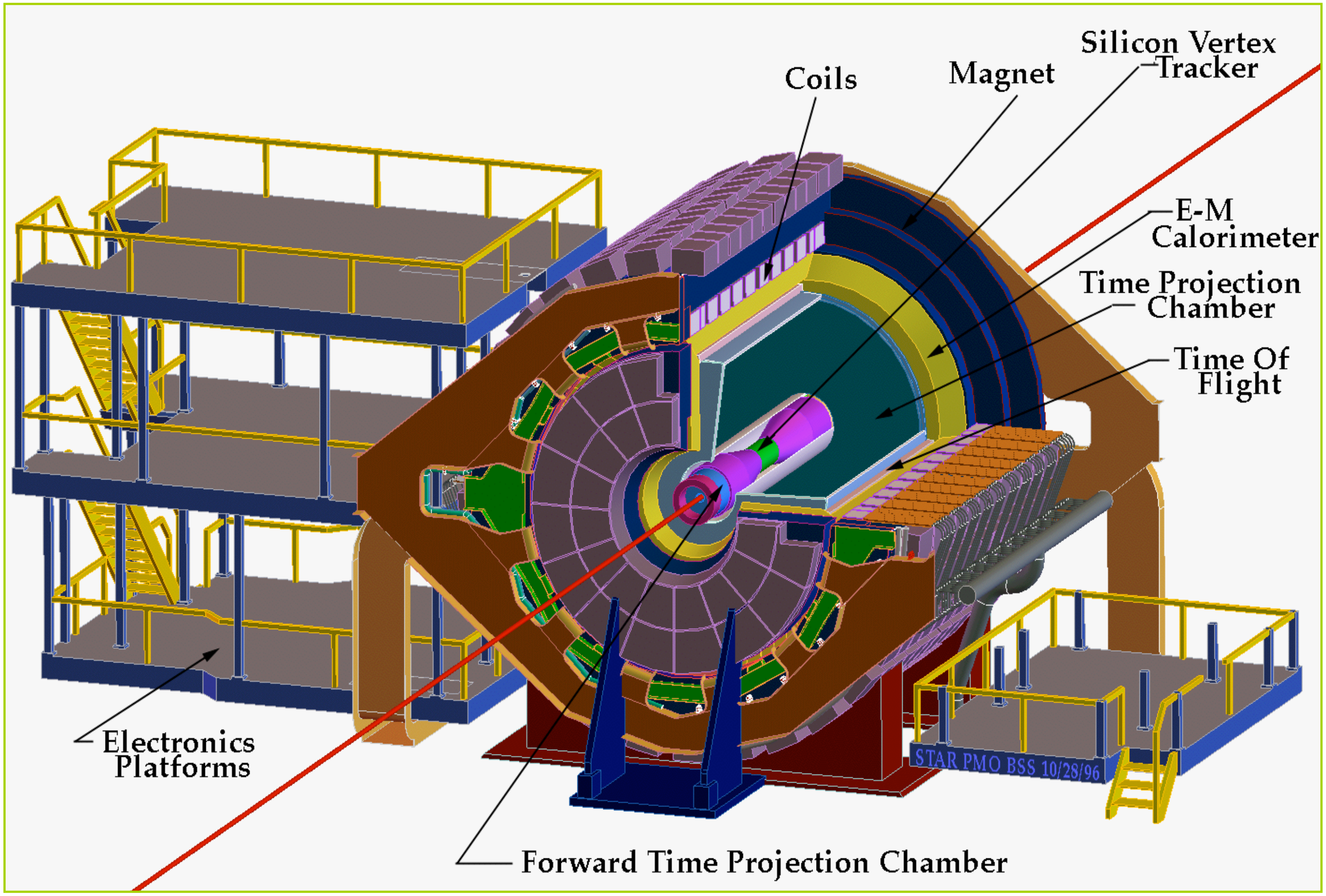
A macroscopic treatment requires that the scattering rate is larger than macroscopic rates

Relativistic **H**eavy **I**on **C**ollider (RHIC)

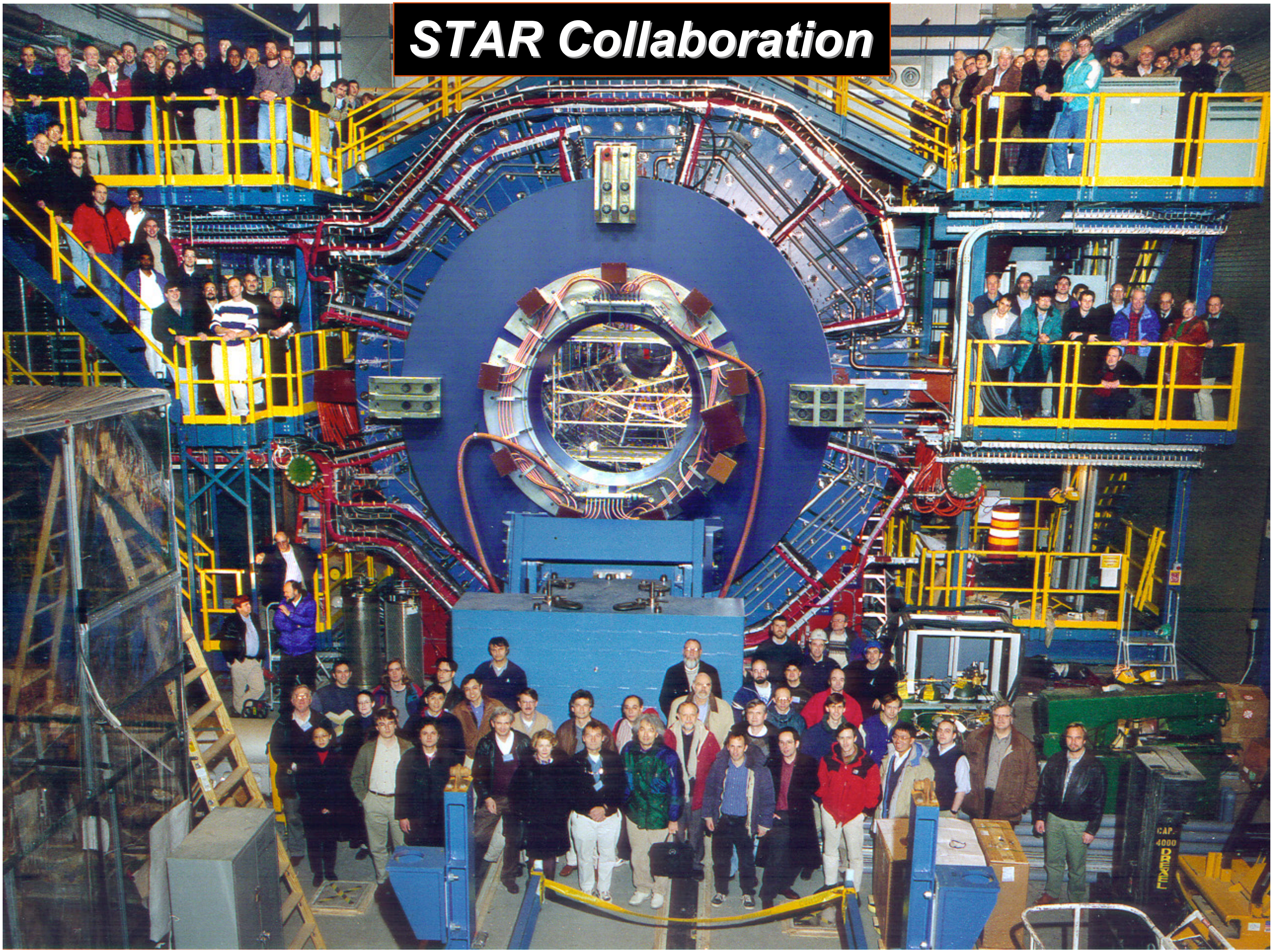
Brookhaven National Laboratory (BNL), Upton, NY



STAR Detectors

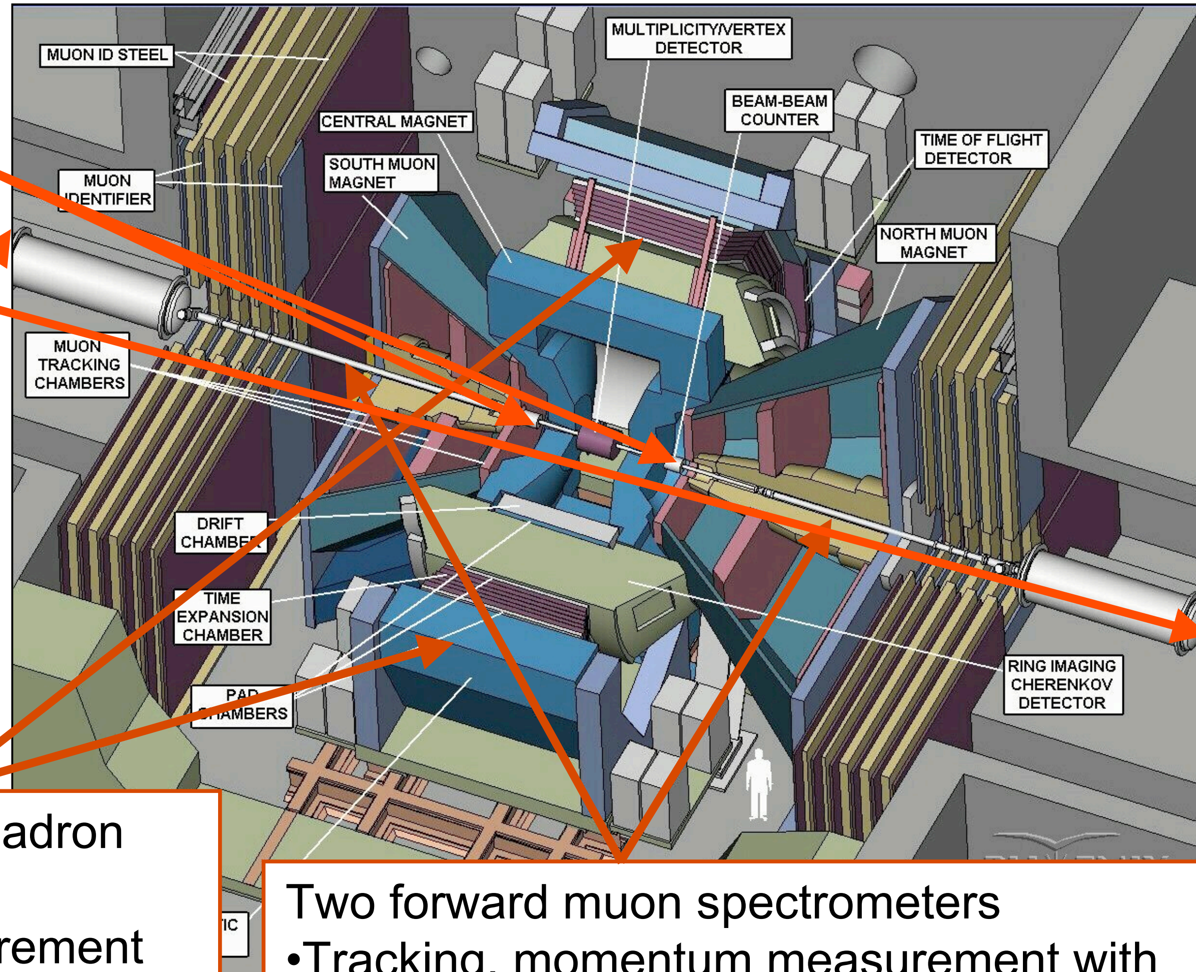


TPC dE/dx PID:
pion/kaon: p_T ~ 0.6 GeV/c; proton p_T ~ 1.2 GeV/c


STAR Collaboration

PHENIX Detectors

Two sets of forward-rapidity detectors for event characterization
Beam-beam counters measure particle production in $3.0<|\eta|<3.9$.
Luminosity monitor + vertex determination.
Zero-degree calorimeters measure forward-going neutrons.
Correlation gives centrality



Two central electron/photon/hadron spectrometers:
•Tracking, momentum measurement with drift chamber, pixel pad chambers
•e ID with E/p ratio in EmCAL + good ring in RICH counter.

Two forward muon spectrometers
•Tracking, momentum measurement with cathode strip chambers
• m ID with penetration depth / momentum match

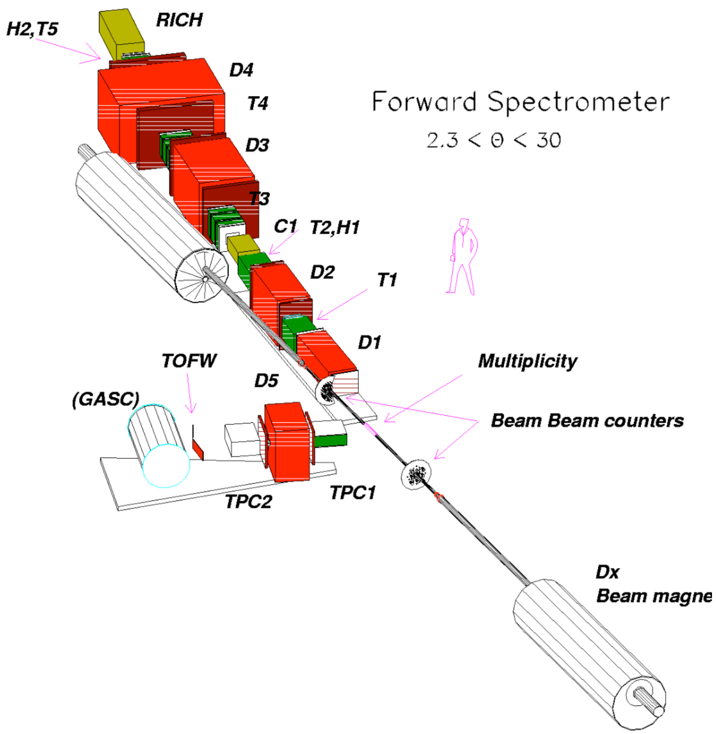
The Two Smaller Detectors

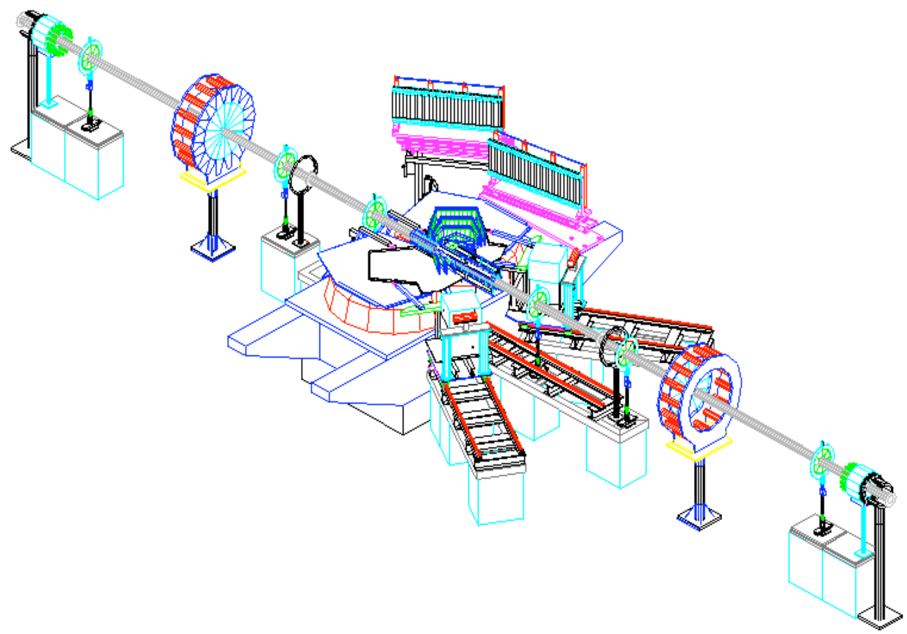
BRAHMS

2 “conventional” spectrometers
full phase space coverage
Magnets, TPCs, TOF, RICH
~40 participants

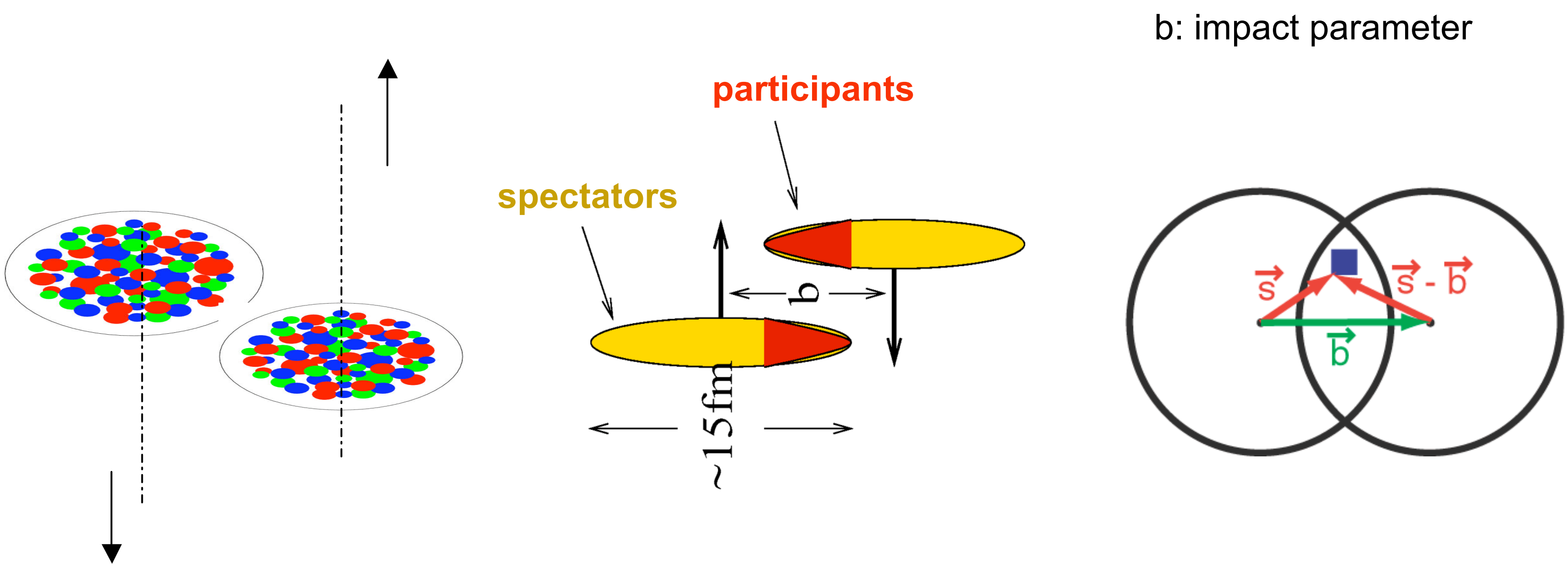
PHOBOS

“Table-top” 2-arm spectrometer
full phase space multiplicity measurement
Magnet, Si μ-strips, Si multiplicity rings, TOF
~80 participants





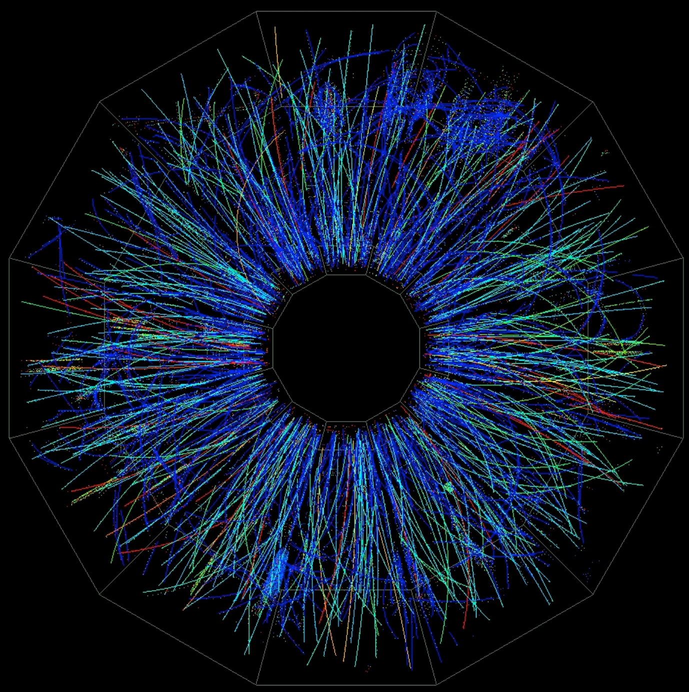
Collision Geometry



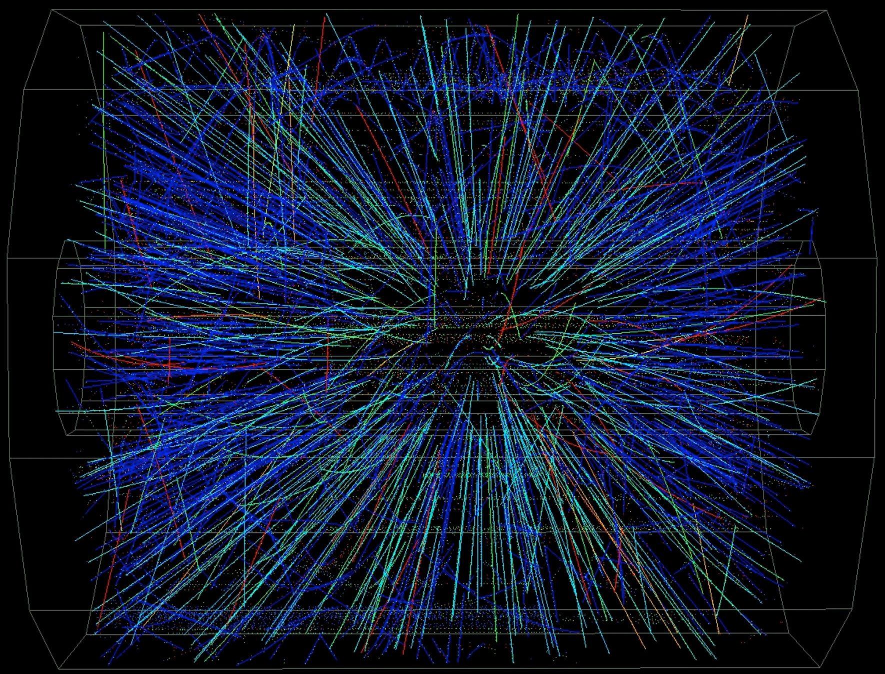
Top-View

End-View

Au + Au Collisions at 130 GeV

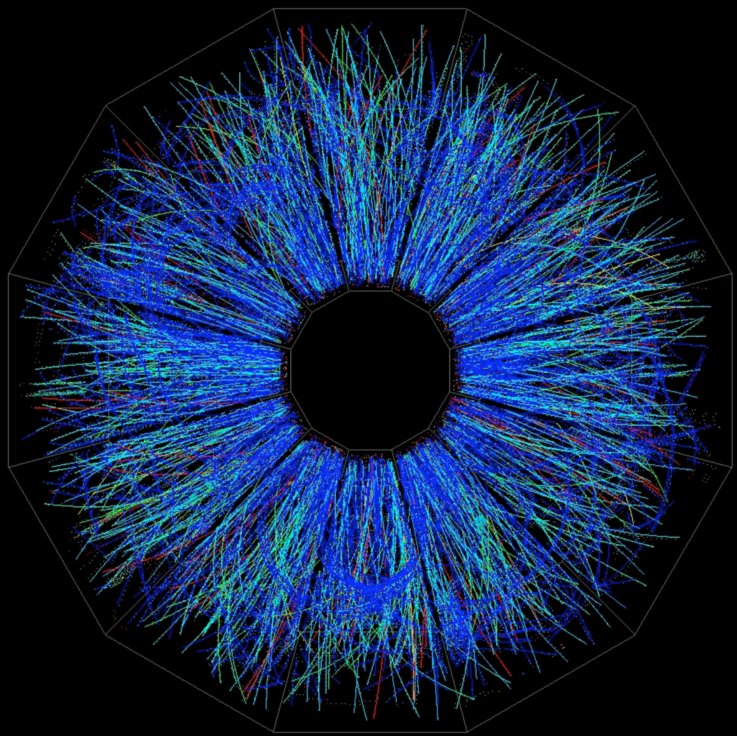


Peripheral Event

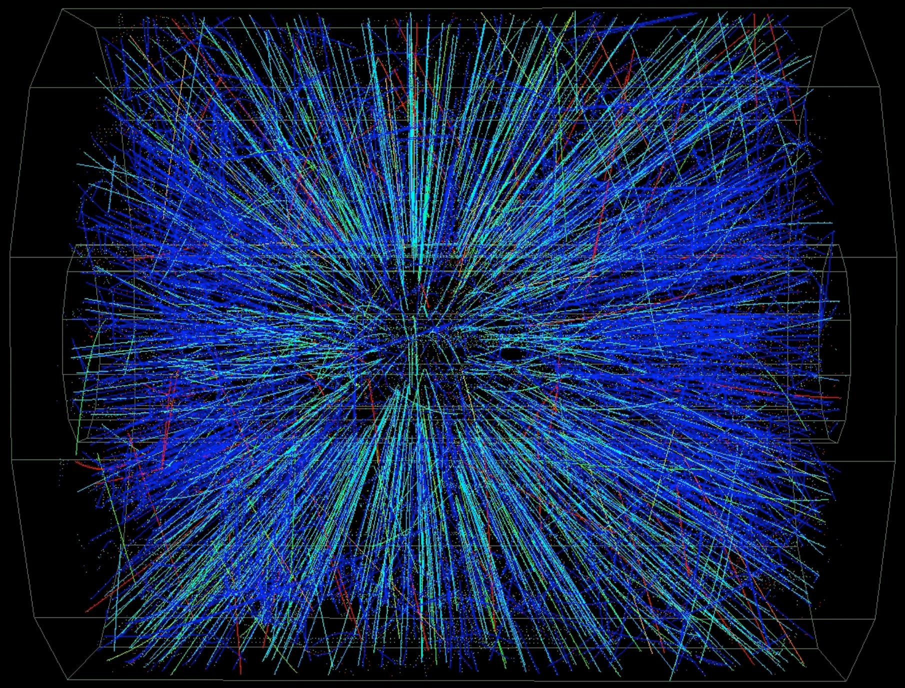


STAR (real-time Level 3)

Au + Au Collisions at 130 GeV

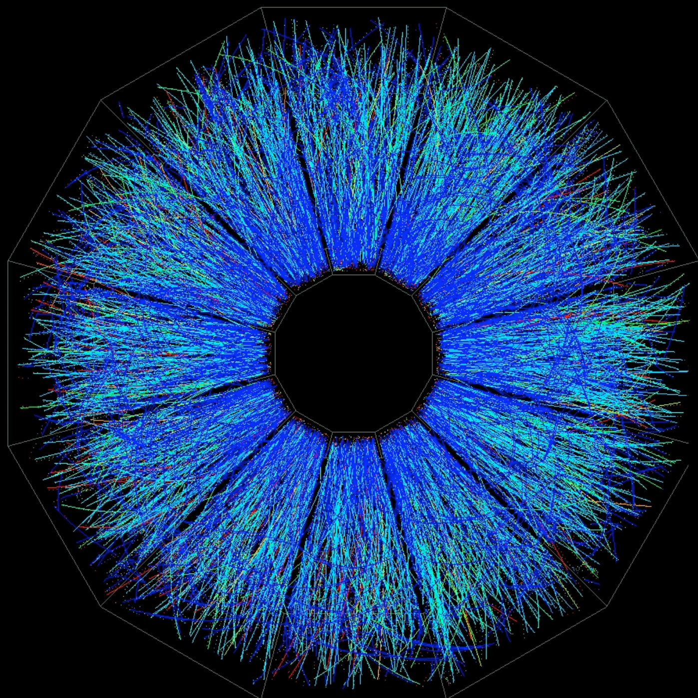


Mid-Central Event

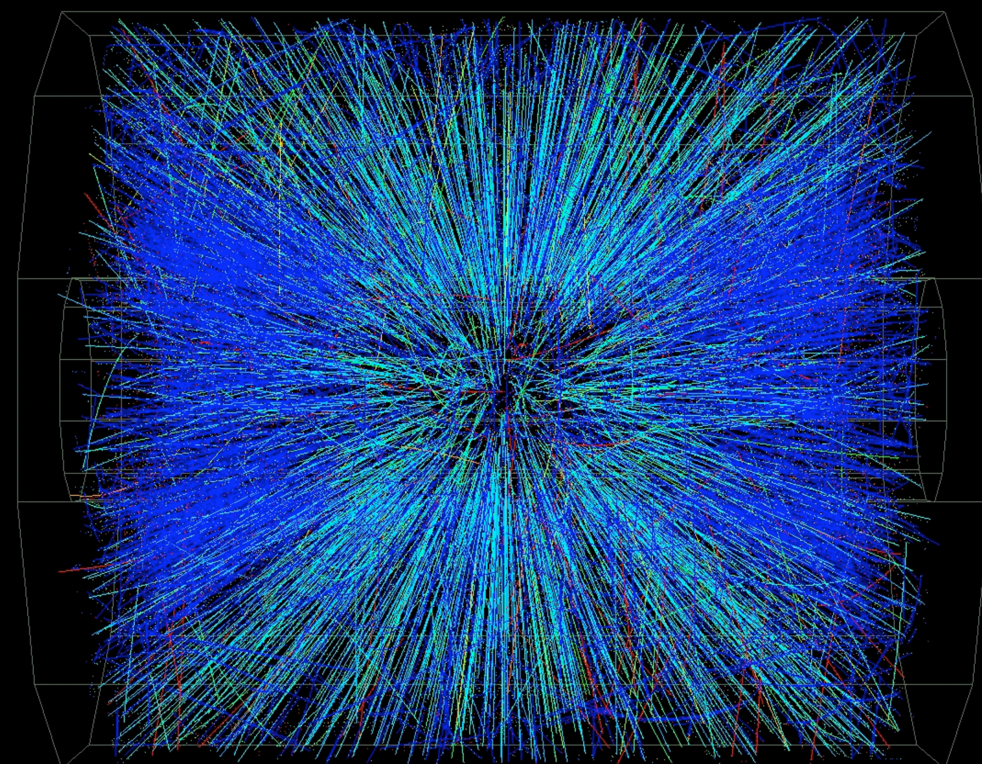


STAR (real-time Level 3)

Au + Au Collisions at RHIC

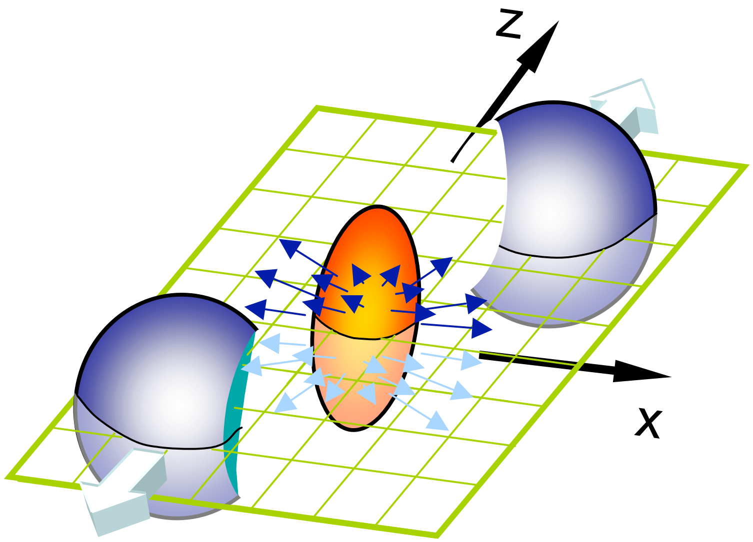


Central Event

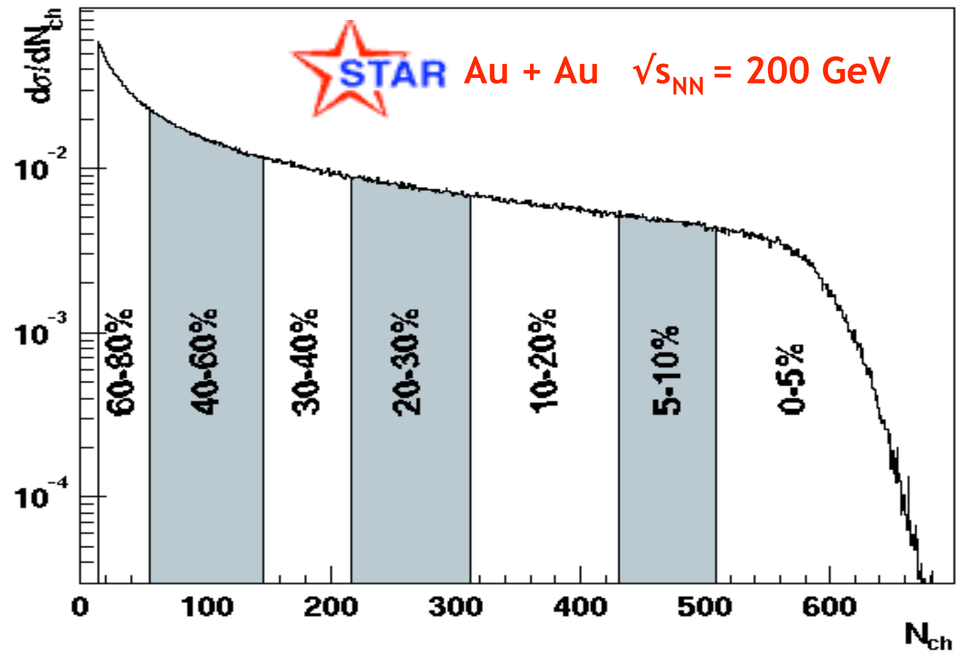


STAR (real-time Level 3)

Collision Geometry



Non-central Collisions



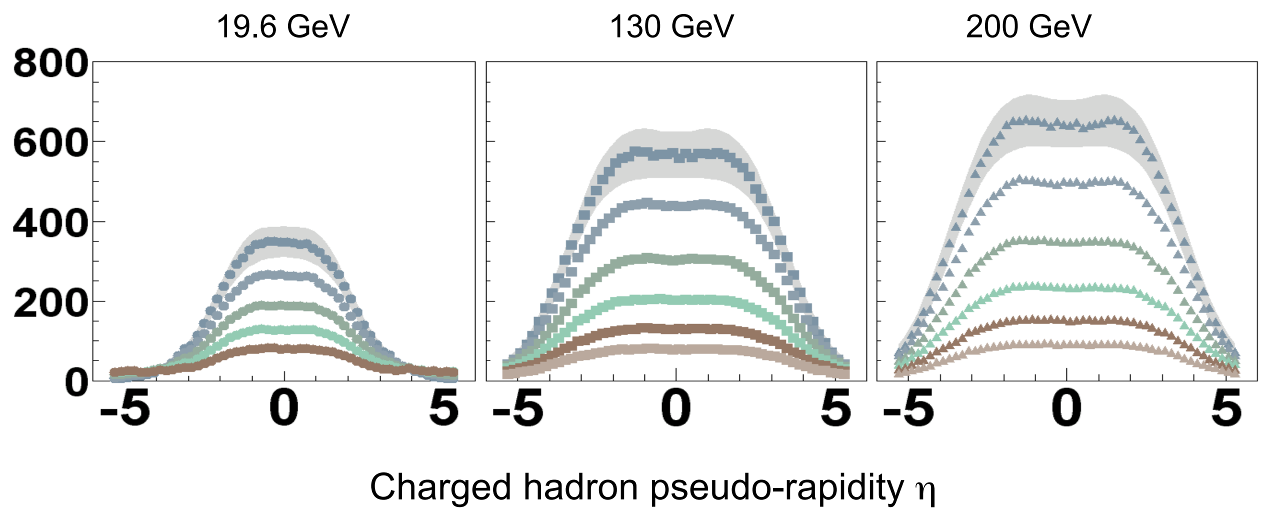
Uncorrected

Number of participants: number of incoming nucleons in the overlap region
Number of binary collisions: number of inelastic nucleon-nucleon collisions

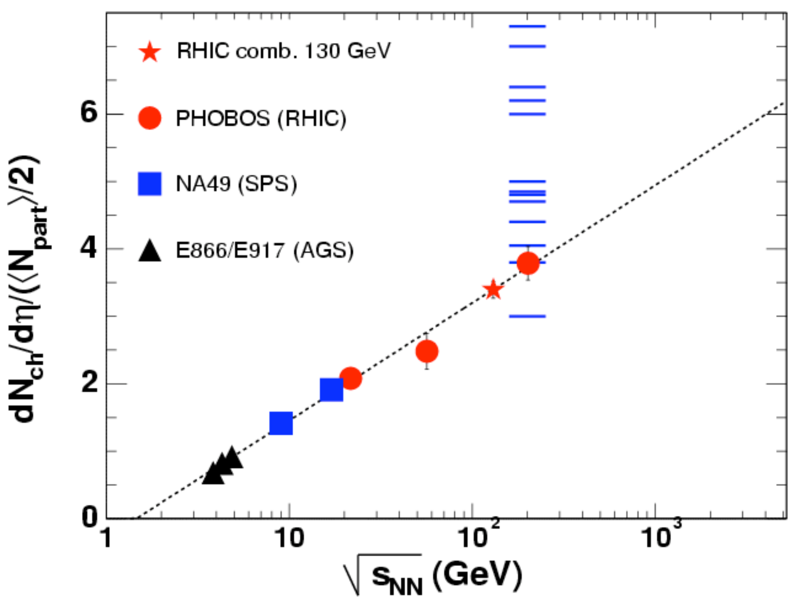
Charged particle multiplicity ⇔ collision centrality

Reaction plane: x-z plane

Global: Charge Hadron Density



PHOBOS Collaboration

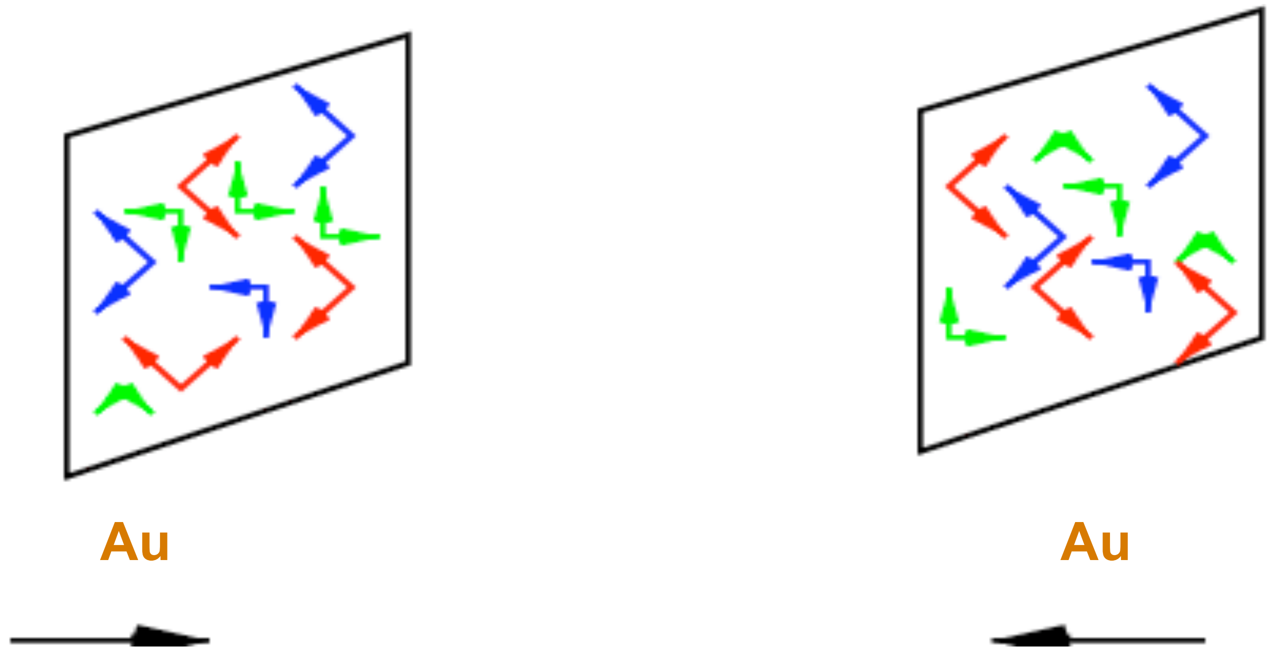


1) High number of N_{ch} indicates initial high density;
2) Mid-y, $N_{ch} \propto N_{part}$ ➪ nuclear collisions are not incoherent;

Important for high density and thermalization.

*PRL **85**, 3100 (00); **91**, 052303 (03); **88**, 22302 (02), **91**, 052303 (03)*

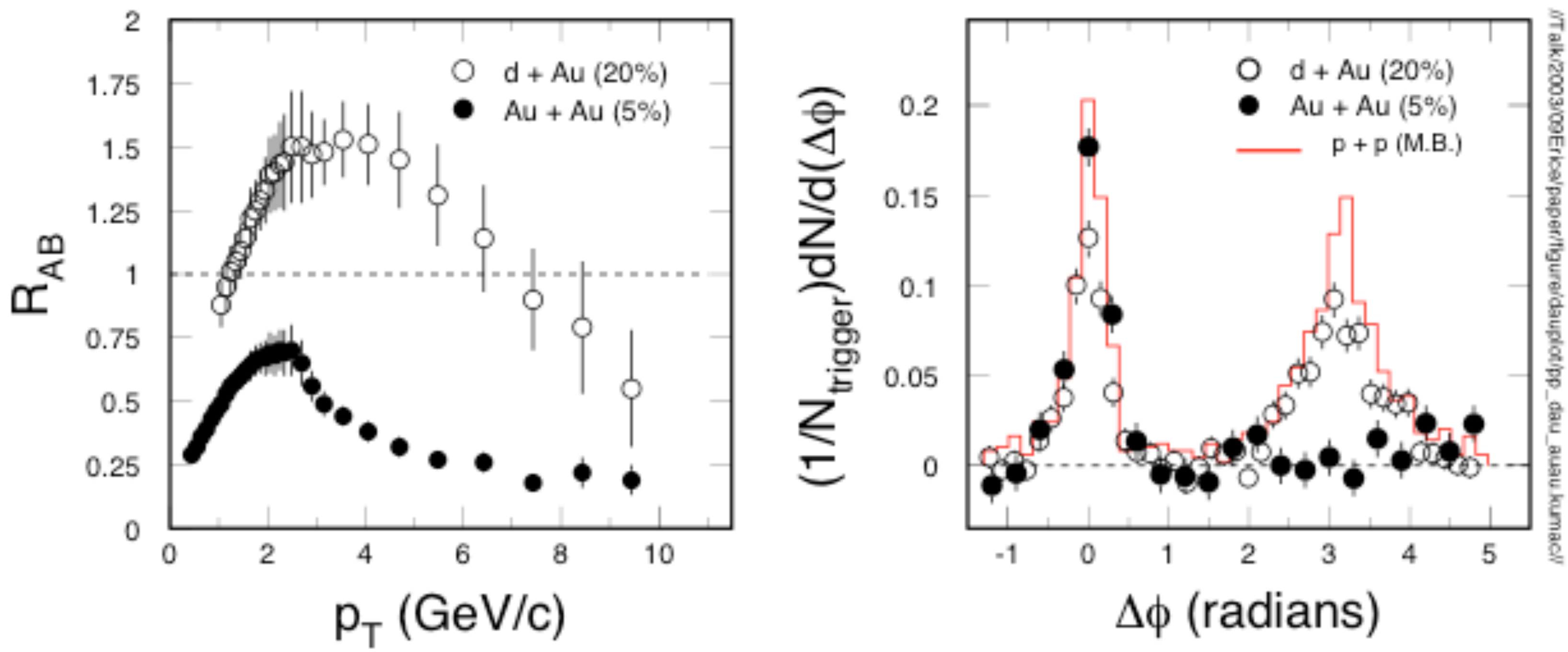
Color Glass Condensate



Random Electric & Magnetic Weizsacker-Williams fields in the plane of the fast moving nucleus

A possible state for the initial conditions at RHIC

Suppression and Correlation



In central Au+Au collisions: hadrons are suppressed and back-to-back 'jets' are disappeared. Different from p+p and d+Au collisions.

Energy density at RHIC: ε > 5 GeV/fm^3 ~ 30ε_0

Parton energy loss:	Bjorken	1982
("**Jet quenching**")	Gyulassy & Wang	1992

…

Transverse Flow Observables

$$\frac{d\vec{\sigma}}{d\Omega} = \frac{d^3\sigma}{dp_x dp_y dp_z} = \frac{dN}{p_t dp_t dy d\varphi} = \frac{1}{2\pi}\frac{dN}{p_t dp_t dy}\left[1 + \sum_{i=1} 2v_i \cos(i\varphi)\right]$$

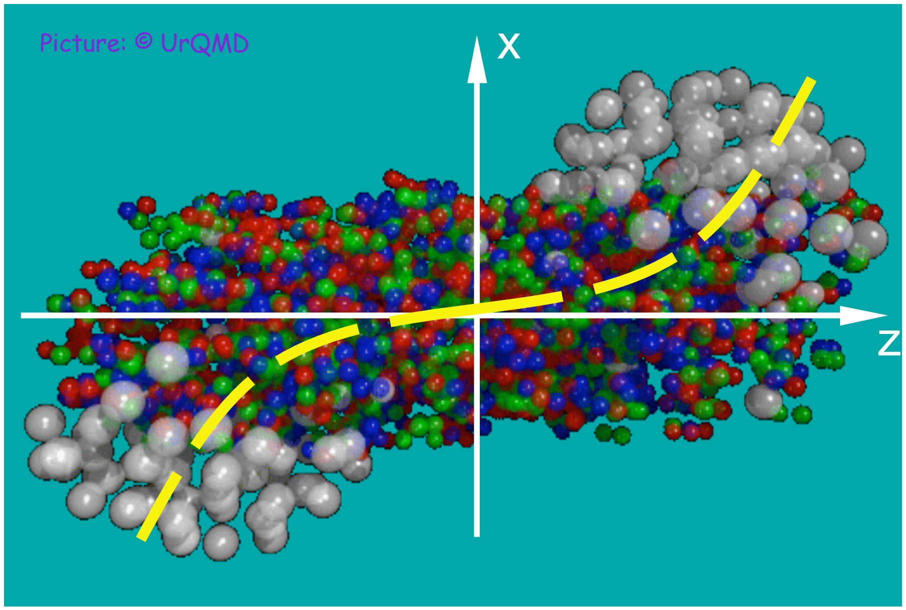
$$p_t = \sqrt{p_x^2 + p_y^2}, \qquad m_t = \sqrt{p_t^2 + m^2}$$

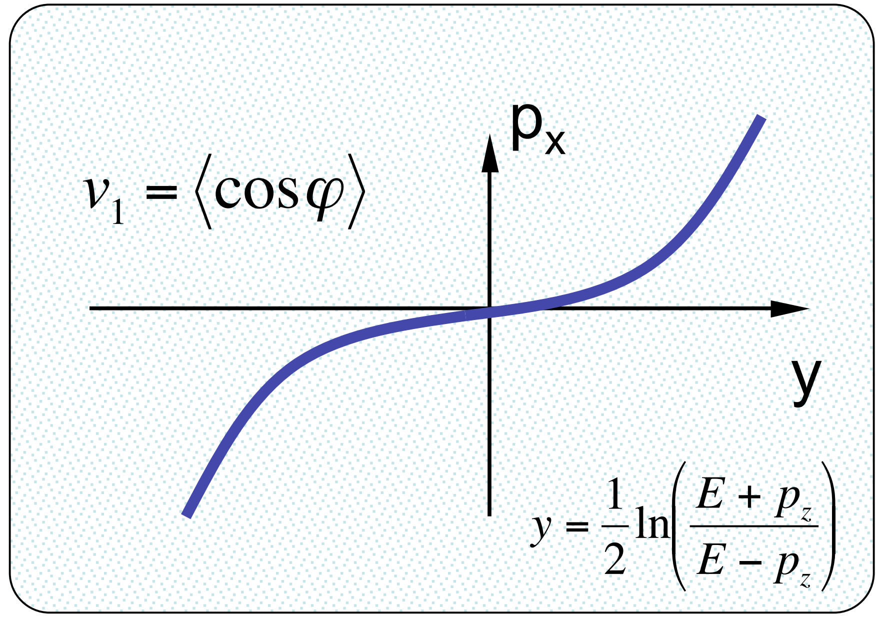
$$v_i = \langle \cos(i\varphi) \rangle_{event} \qquad \varphi = \tan^{-1}\left(\frac{p_y}{p_x}\right)$$

1) Radial flow – integrated over whole period of evolution
2) Directed flow (v_1) – relatively early
3) Elliptic flow (v_2) – relatively early

- Hadron mass dependent: characteristic of hydrodynamic behavior.

Directed Flow v_1

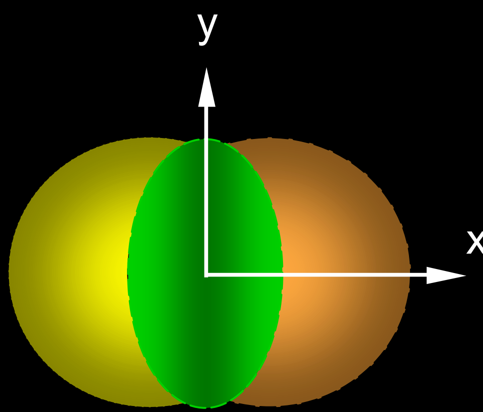


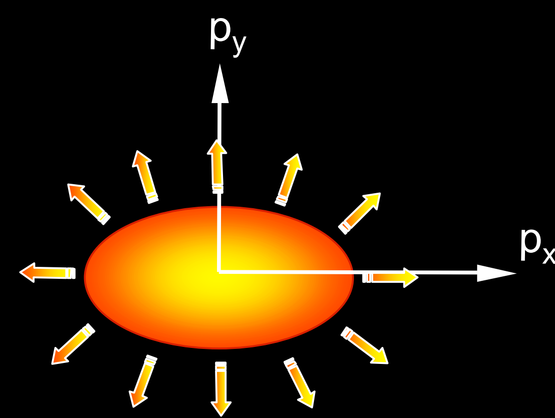


Initial spatial anisotropy ➠ **Anisotropy in momentum space**

Anisotropy Parameter v_2

coordinate-space-anisotropy ➪ momentum-space-anisotropy

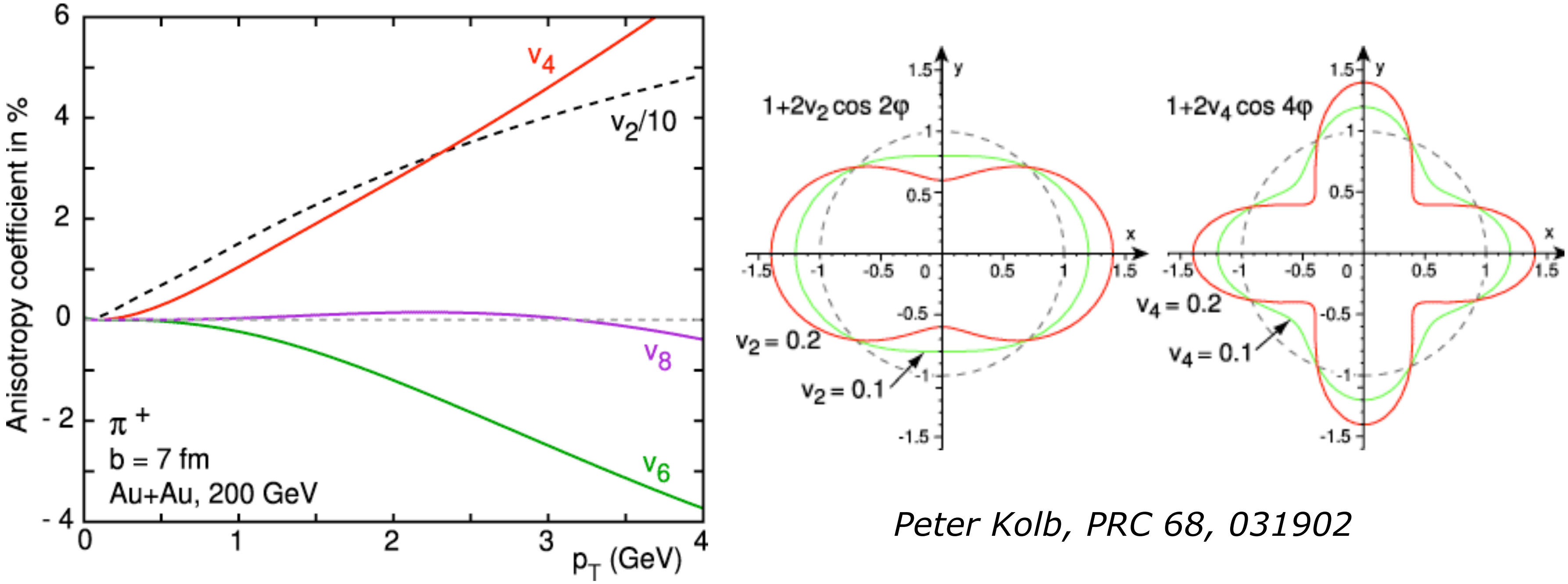




$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle} \qquad v_2 = \langle \cos 2\varphi \rangle, \quad \varphi = \tan^{-1}\left(\frac{p_y}{p_x}\right)$$

Initial/final conditions, EoS, degrees of freedom

Higher Harmonics



Peter Kolb, PRC 68, 031902

- Higher harmonics are expected to be present. For smooth azimuthal distributions the higher harmonics will be small $v_n \sim v_2^{n/2}$
- **v_4** - a small, but sensitive observable for heavy ion collisions.

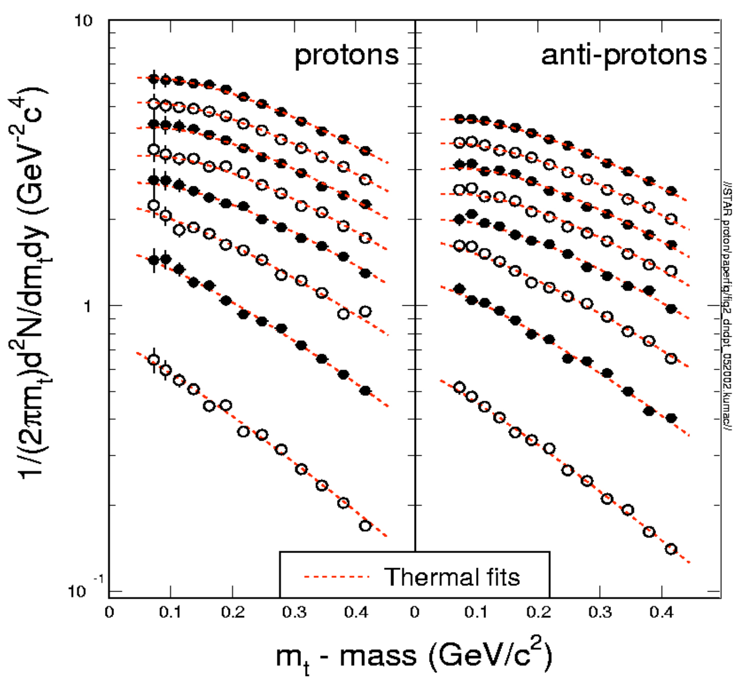
  P. Kolb, PR ***C68****, 031902(04)*
- **v_4** - magnitude sensitive to ideal hydro behavior.

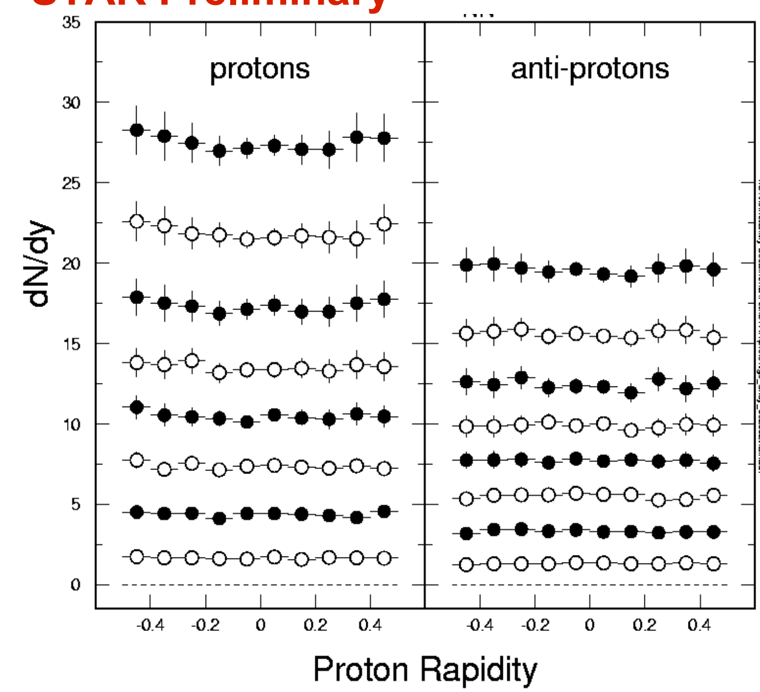
  Borghini and Ollitrault, nucl-th/0506045

Protons From RHIC

K. Schweda, M. Kaneta …

130 GeV Au + Au Collisions
STAR Preliminary



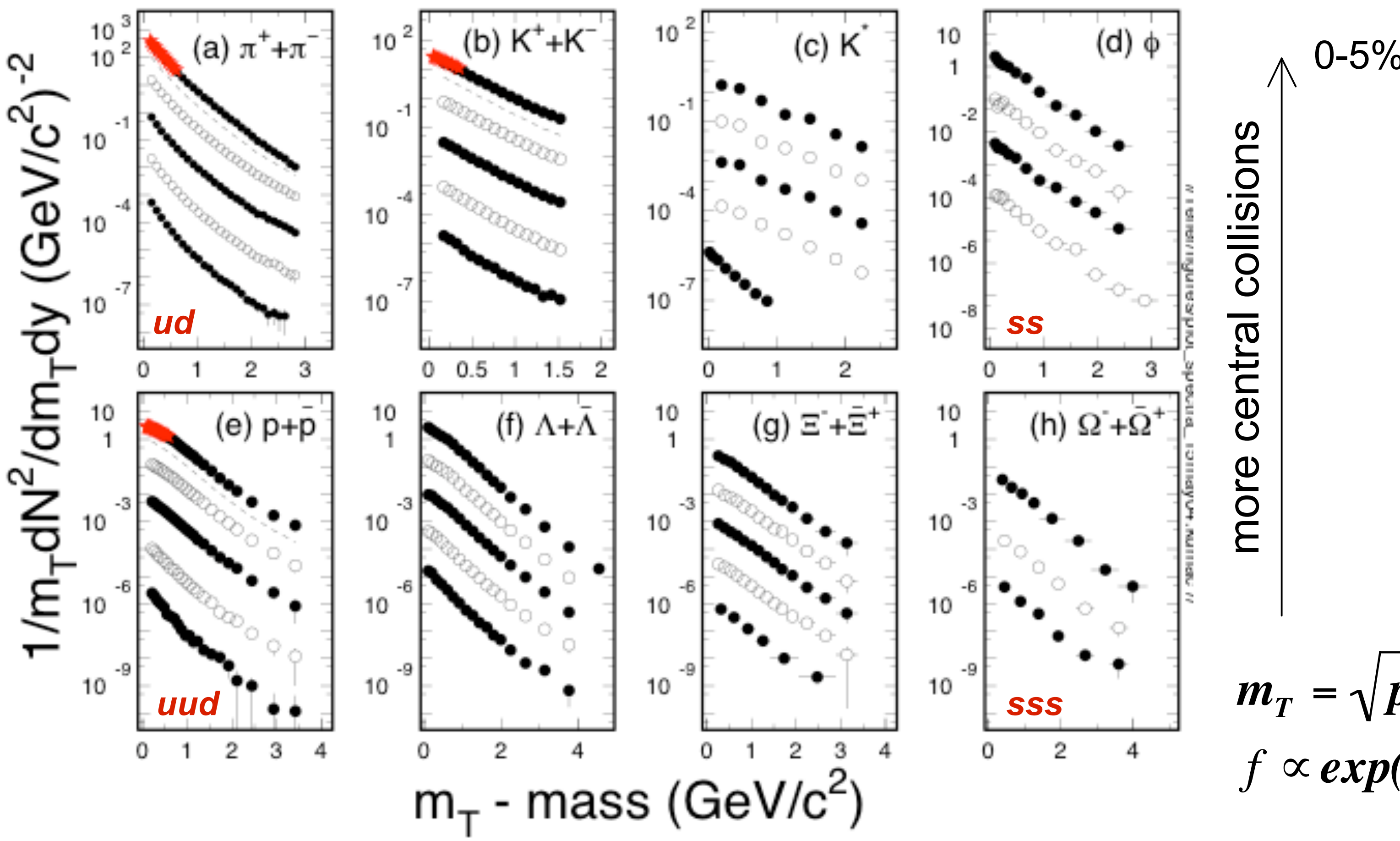


1) **In central collisions, m_t distributions become more concave $\Rightarrow$ collective flow !**

2) **Within $|y|<0.5$, dN/dy and $<p_T>$ are flat $\Rightarrow$ boost invariant !**

Hadron Spectra from RHIC

p+p and Au+Au collisions at 200 GeV



$$m_T = \sqrt{p_T^2 + m^2}$$

$$f \propto exp(-m_T/T_{slope})$$

Multi-strange hadron spectra are exponential in their shapes.

STAR white papers - Nucl. Phys. A757, 102(2005).

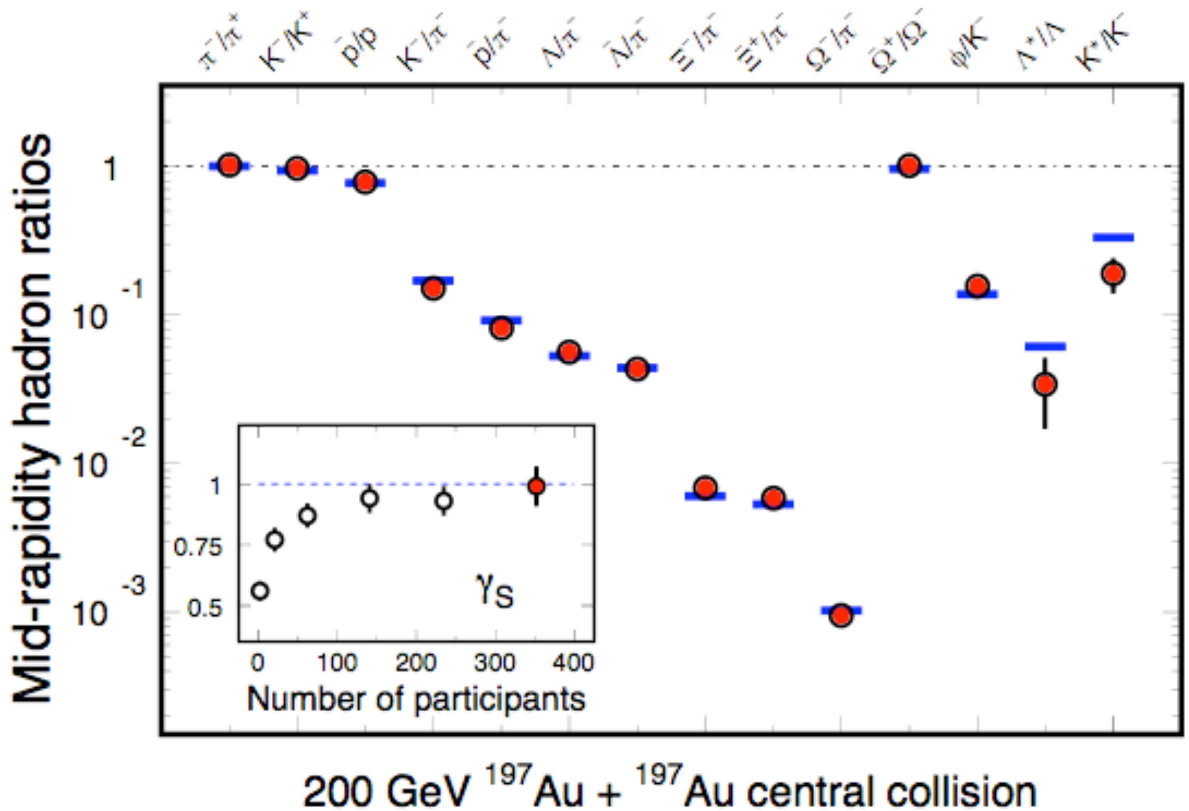
The Basic Ideas

- Assume thermally (constant T_{ch}) and chemically (constant n_i) equilibrated system at chemical freeze-out
- System composed of non-interacting hadrons and resonances
- Given T_{ch} and m 's (+ system size), n_i's can be calculated in a grand canonical ensemble

$$n_i = \frac{g}{2\pi^2}\int_0^\infty \frac{p^2 dp}{e^{(E_i(p)-\mu_i)/T} \pm 1}, \quad E_i = \sqrt{p^2 + m_i^2}$$

- Obey conservation laws: Baryon Number, Strangeness, Isospin
- Short-lived particles and resonances need to be taken into account

Yields Ratio Results



data

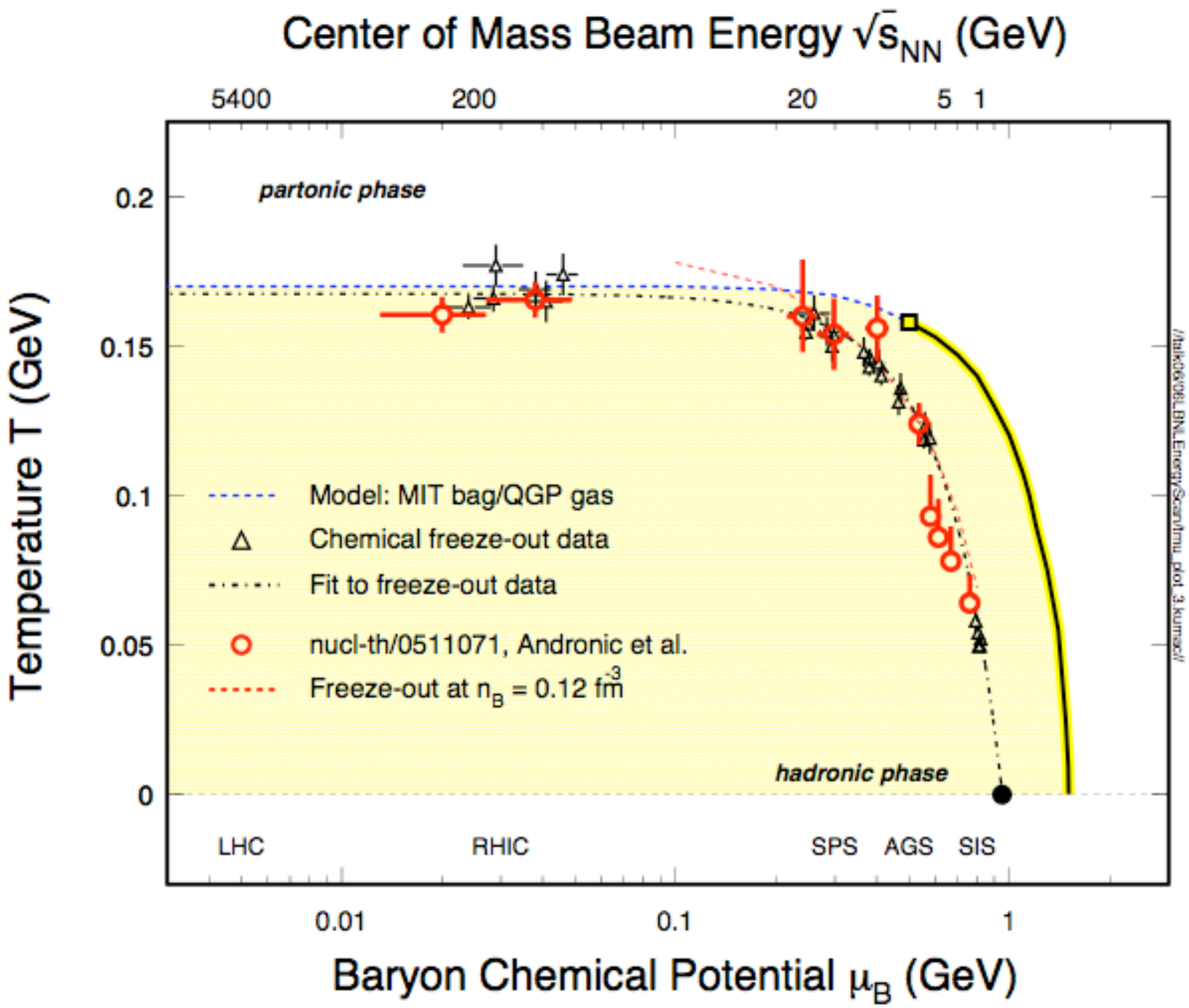
Thermal model fits

T_{ch} = 163 ± 4 MeV

μ_B = 24 ± 4 MeV

- In central collisions, thermal model fit well with γ_S = 1. **The system is thermalized at RHIC.**
- Short-lived resonances show deviations. **There is life after chemical freeze-out.** RHIC white papers - 2005, Nucl. Phys. <u>A757</u>, STAR: p102; PHENIX: p184.

QCD Phase Diagram



Thermal Model Fits (Blast-Wave)

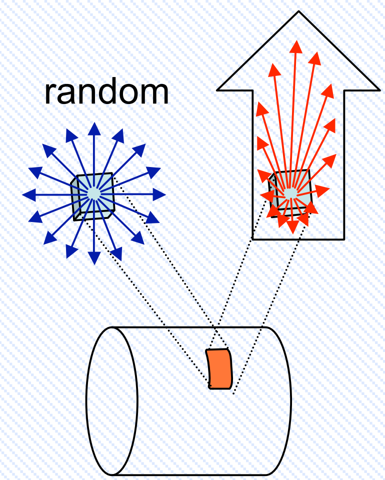
Source is assumed to be:
- Locally thermal equilibrated
- Boosted in radial direction

*E.Schnedermann, J.Sollfrank, and U.Heinz, Phys. Rev. **C48**, 2462(1993)*

$$E\frac{d^3N}{dp^3} \propto \int_\sigma e^{-(u^\mu p_\mu)/T_{fo}} p d\sigma_\mu \Rightarrow$$

$$\frac{dN}{m_T dm_T} \propto \int_0^R r dr m_T K_1\left(\frac{m_T \cosh\rho}{T_{fo}}\right) I_0\left(\frac{p_T \sinh\rho}{T_{fo}}\right)$$

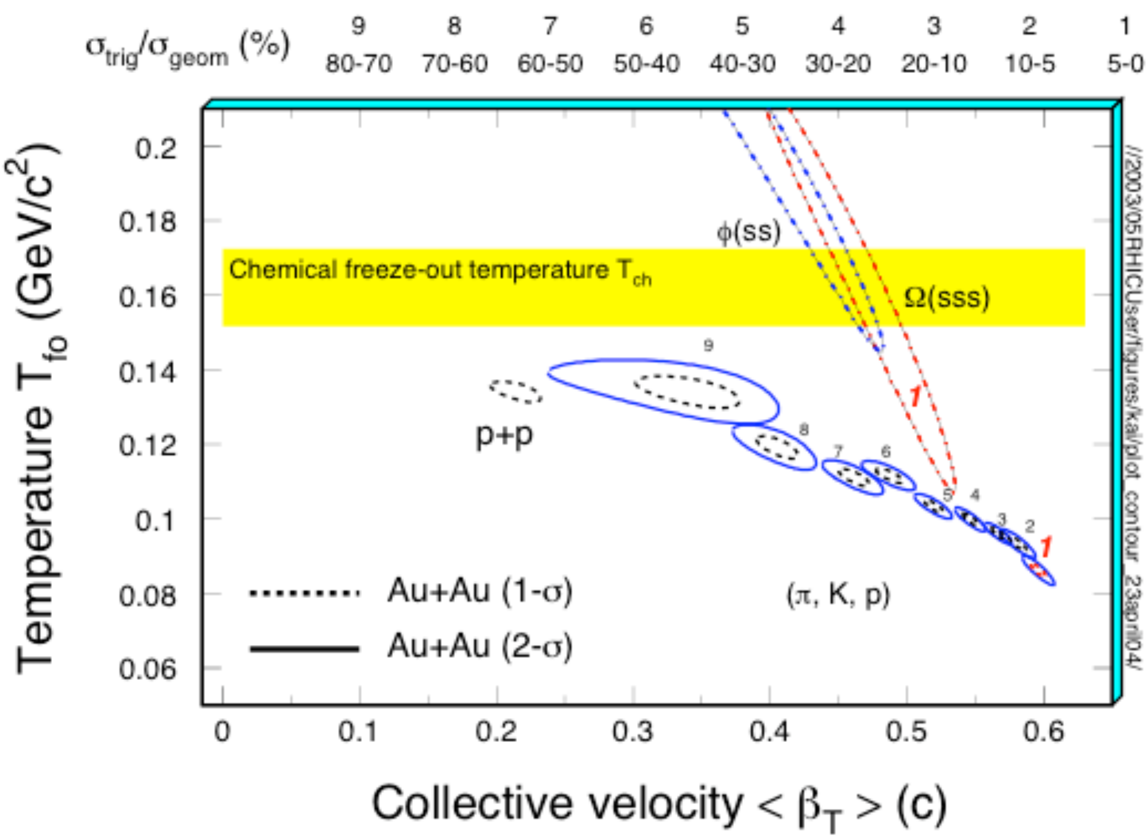
$$\rho = \tanh^{-1}\beta_T \qquad \beta_T = \beta_S\left(\frac{r}{R}\right)^\alpha \qquad \alpha = 0.5,\ 1,\ 2$$



Extract thermal temperature T_{fo} and velocity parameter $\langle\beta_T\rangle$

Blast Wave Fits: T_{fo} vs. $\langle\beta_T\rangle$

200GeV Au + Au collisions



1) π, *K*, and *p* change smoothly from peripheral to central collisions.

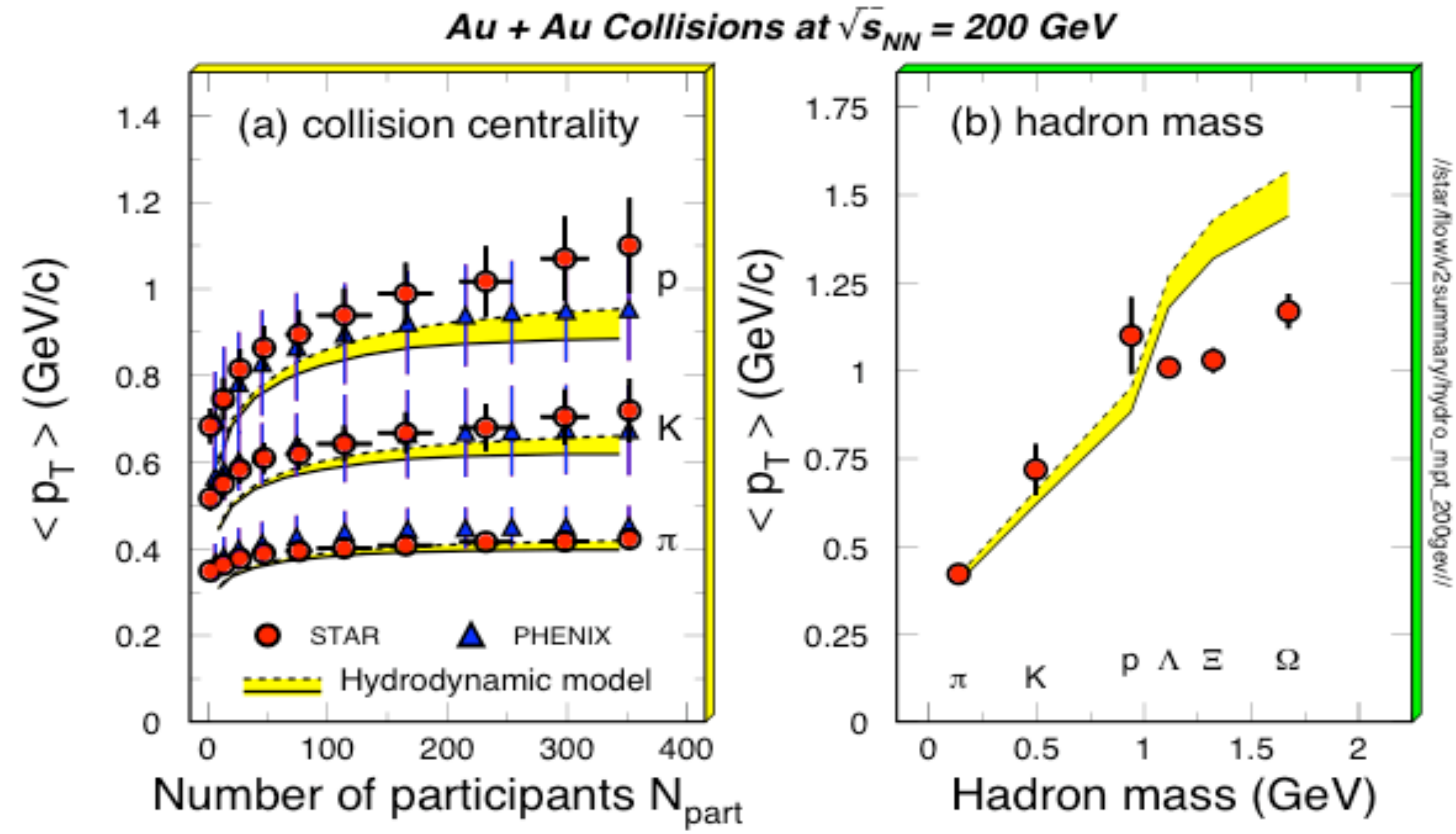
2) At the most central collisions, $\langle\beta_T\rangle$ reaches 0.6c.

3) Multi-strange particles ϕ, Ω are found at higher T_{fo} and lower $\langle\beta_T\rangle$

⇨ **light hadrons move with higher velocity compared to strange hadrons**

STAR: NP**A715**, 458c(03); *PRL* ***92***, *112301(04);* ***92***, *182301(04).*

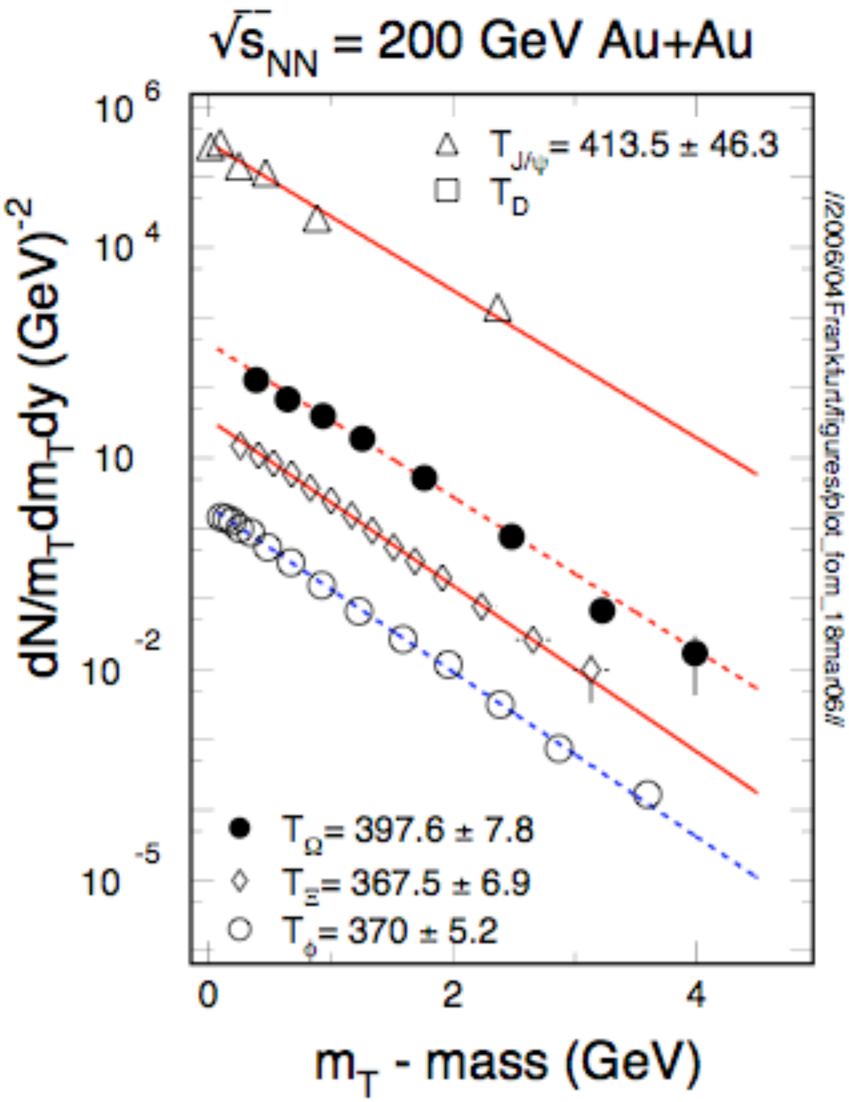
Compare with Model Results



Hydro model works well for *π, K, p*, but over-predicts flow for multi-strange hadrons

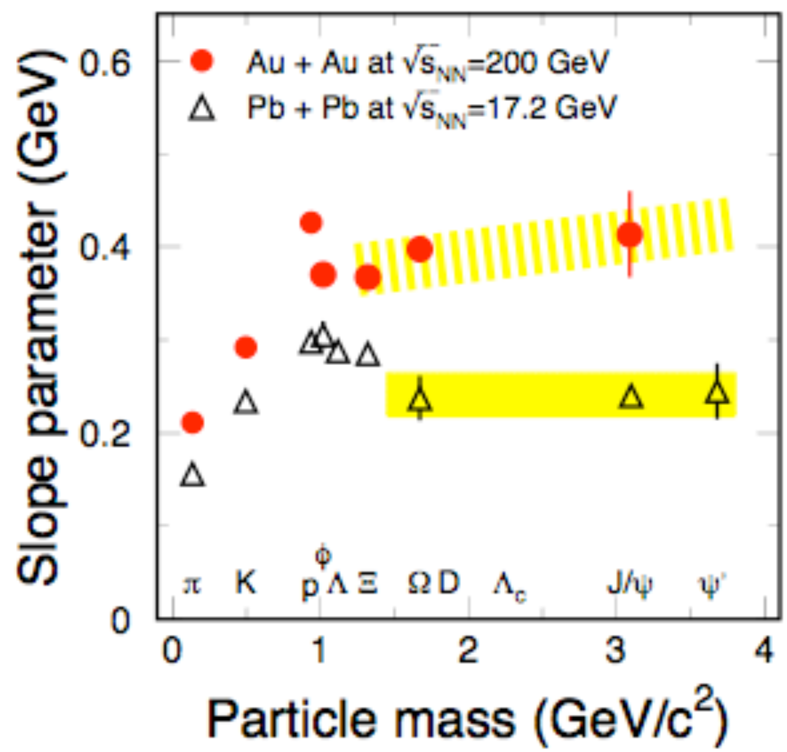
Initial 'collective kick' introduced *(P. Kolb and R. Rapp, PRC67)*

Slope Parameter Systematics

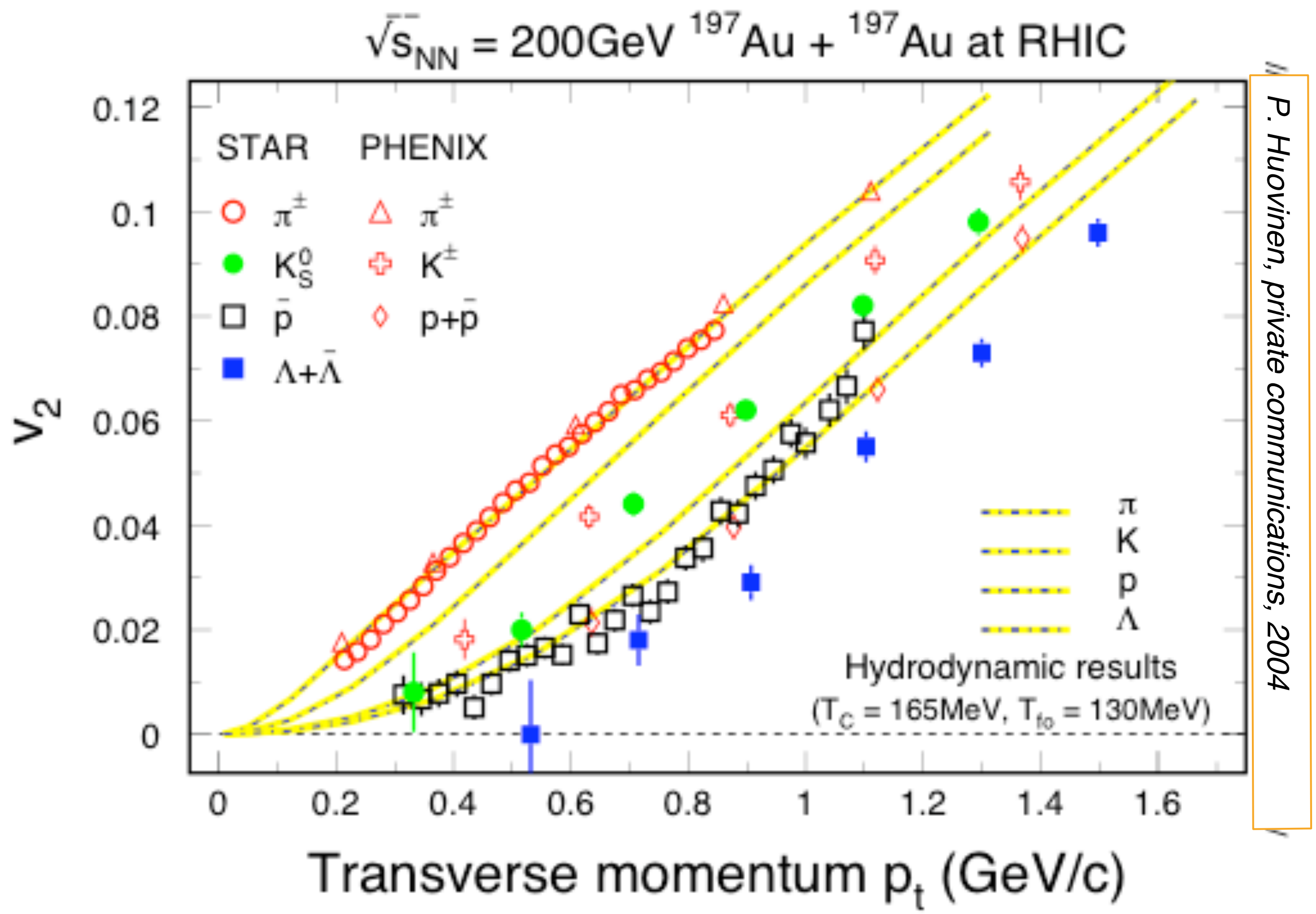


$$m_T = \sqrt{p_T^2 + m^2}$$

$$f \propto exp(-m_T/T_{slope})$$

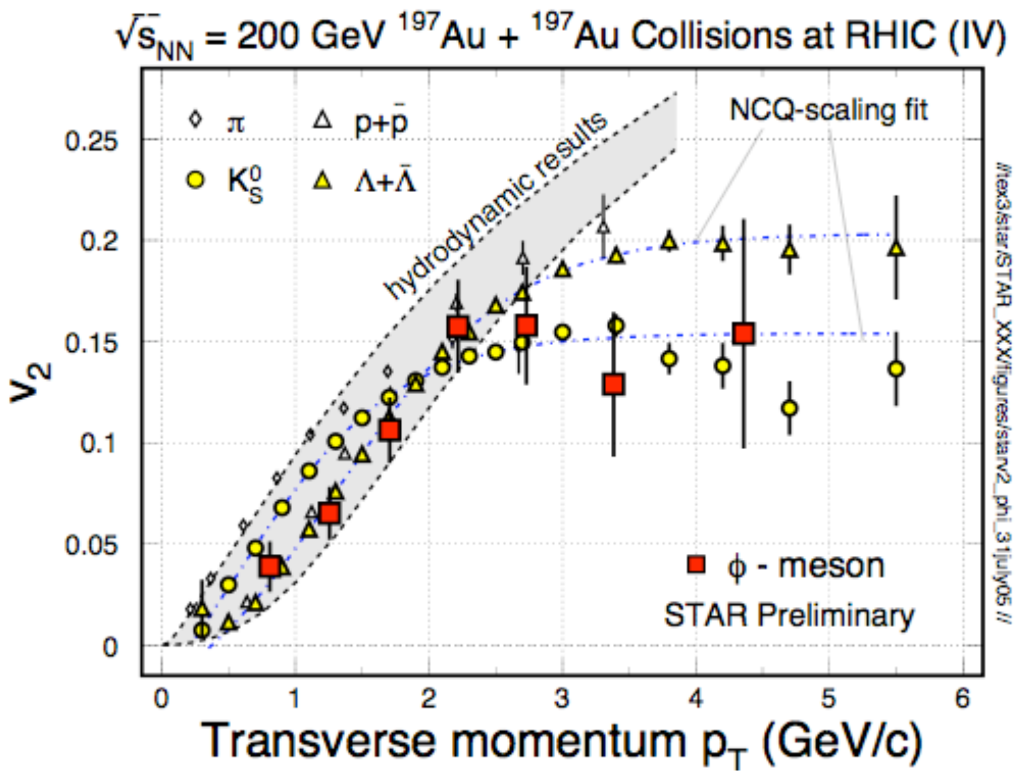


v_2 at Low p_T Region



- Minimum bias data!
- At low p_T, model result fits mass hierarchy well - Collective motion at RHIC
- More work needed to fix the details in the model calculations.

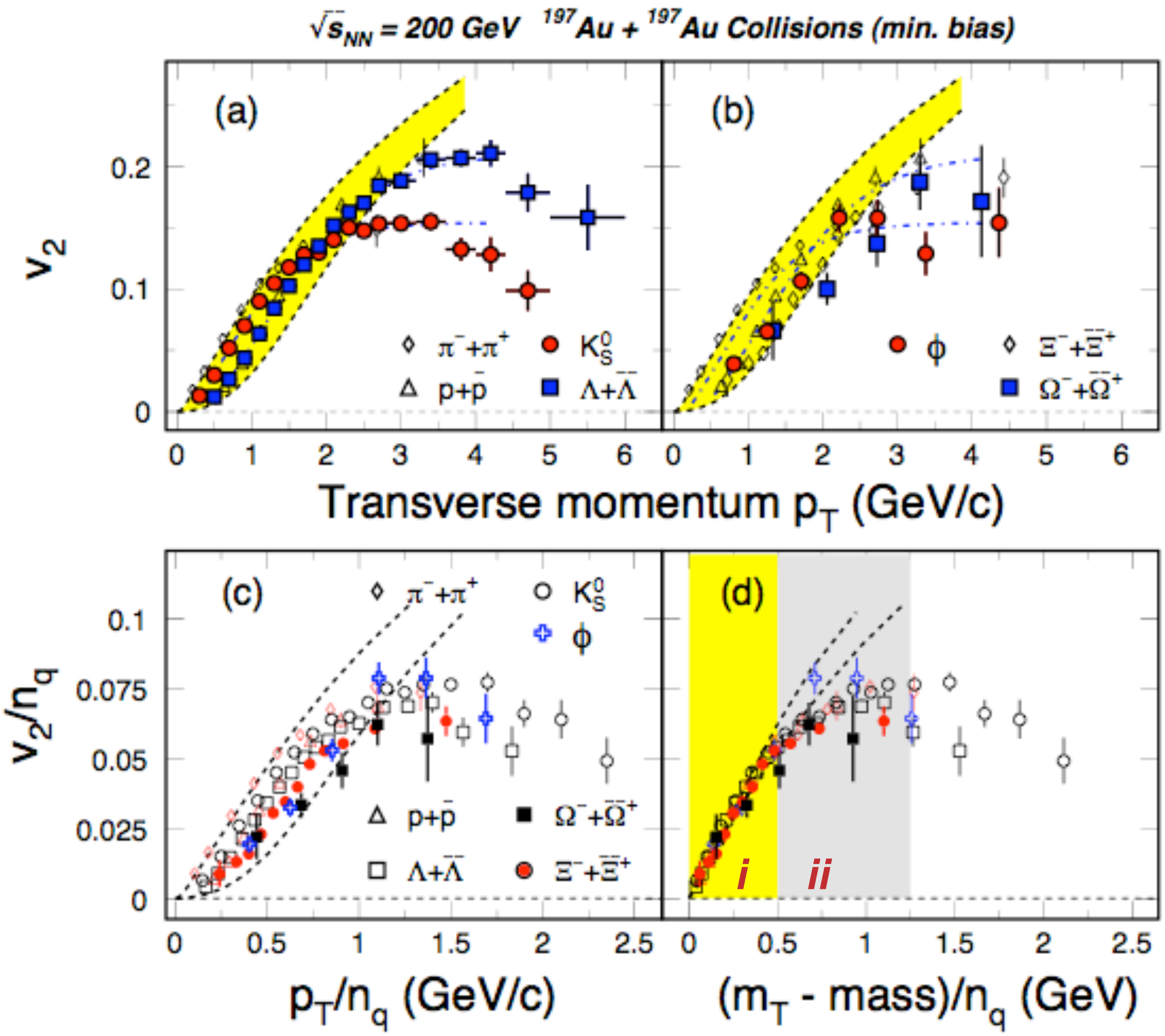
ϕ -mesons Flow: Partonic Flow



ϕ-mesons are very special:
- they do not re-interact in hadronic environment
- they show strong collective flow
- they are formed via coalescence with thermal s-quarks

STAR Preliminary: SQM06, S. Blyth
Hwa and Yang, nucl-th/0602024; Chen et al., PRC73 (2006) 044903

Collectivity, Deconfinement at RHIC



- v_2 of light hadrons and multi-strange hadrons
- scaling by the number of quarks

At RHIC:

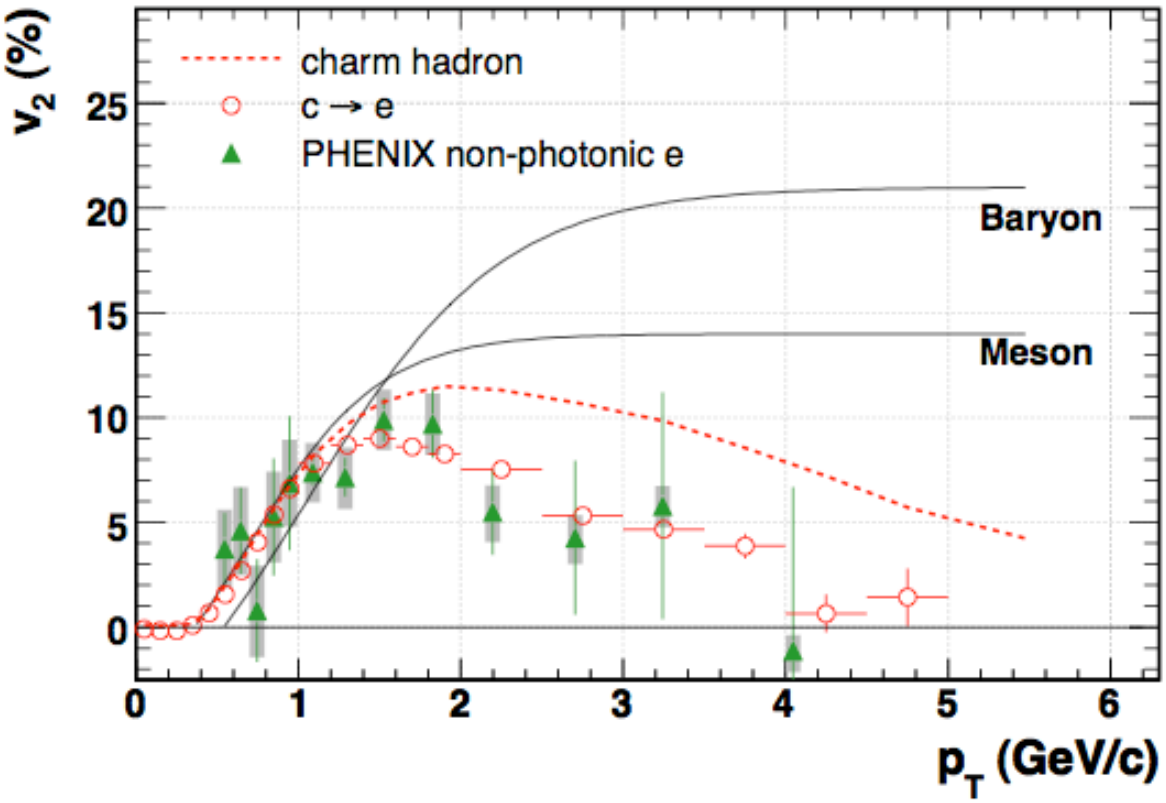
➩ **m_T - NQ scaling**

➩ **De-confinement**

*PHENIX: PRL**91**, 182301(03)*
*STAR: PRL**92**, 052302(04), **95**, 122301(05) nucl-ex/0405022, QM05*

S. Voloshin, NPA715, 379(03)
*Models: Greco et al, PR**C68**, 034904(03)*
Chen, Ko, nucl-th/0602025
*Nonaka et al. **PLB583**, 73(04)*
*X. Dong, et al., Phys. Lett. **B597**, 328(04).*
….

Non-photonic Electron v_2



<u>PHENIX: Minimum bias</u> M. Kaneta *et al*, J.Phys. **<u>G30</u>**, S1217(04)

Yifei Zhang STAR Ph.D student

HSD: E. Bratkovskaya et al., hep-ph/0409071; X. Dong, S. Esumi, et al., Phys. Lett. ***<u>B597</u>****, 328(2004).*

EoS Parameters at RHIC

In central Au+Au collisions at RHIC

- partonic freeze-out:

$^*T_{pfo}$ = 165 ± 10 MeV weak centrality dependence

$v_{pfo} \geq 0.2$ (c)

- hadronic freeze-out:

$^*T_{fo}$ = 100 ± 5 (MeV) strong centrality dependence

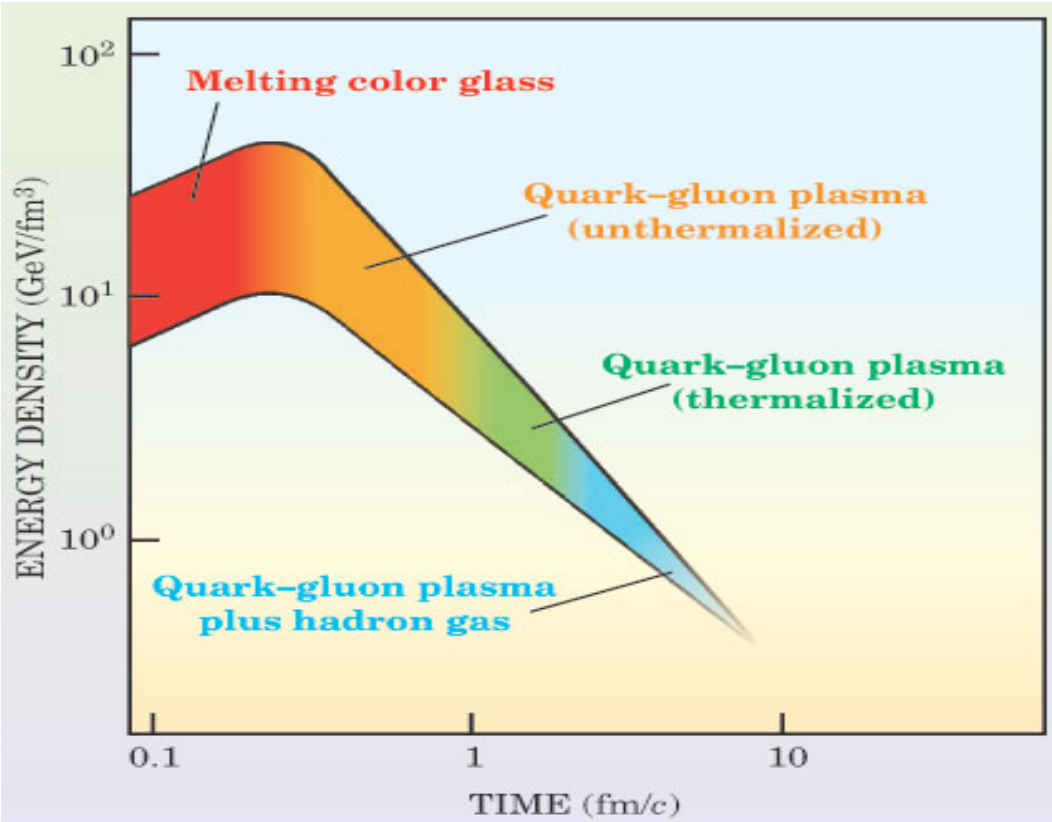
v_{fo} = 0.6 ± 0.05 (c)

Systematic study are needed to understand the centrality dependence of the EoS parameters

** Thermalization assumed*

Summary

Physics Today
L. McLerran, T. Ludlam,



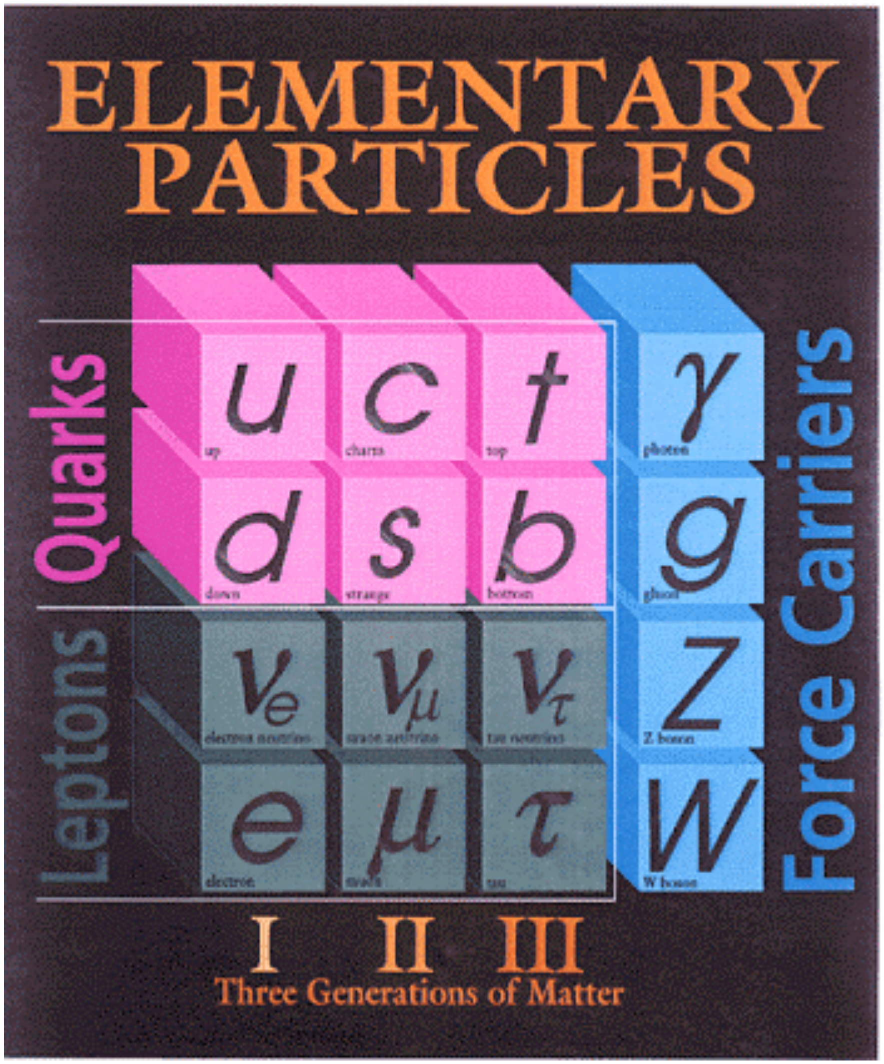
Jet-quenching:
Hot and dense system created in Au+Au collisions

Flow:
Collective flow observed for all hadrons especially the multi-strange and charm hadrons. The partonic interactions are responsible to the early collectivity at RHIC

Next Step:
Test thermalization of light flavors by studying heavy flavor collectivity

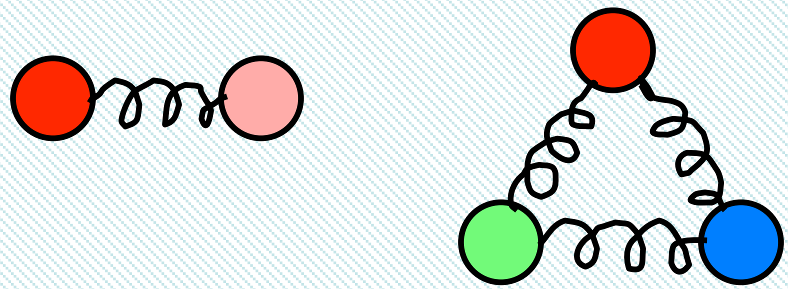
In the Near Future

Quantum Chromodynamics



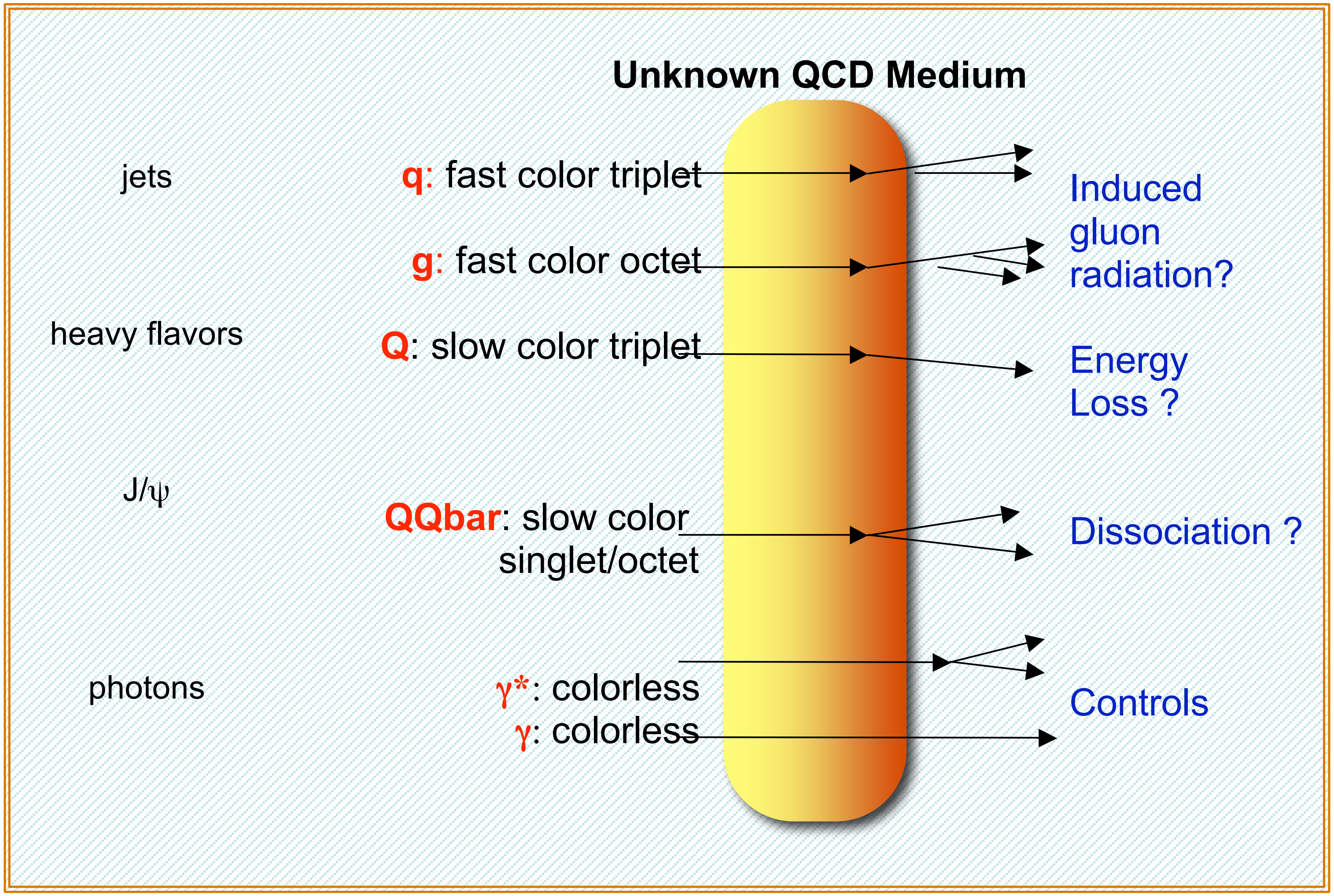
1) Quantum Chromodynamics (QCD) is the established theory of strongly interacting matter.
2) Gluons hold quarks together to from hadrons:

meson baryon



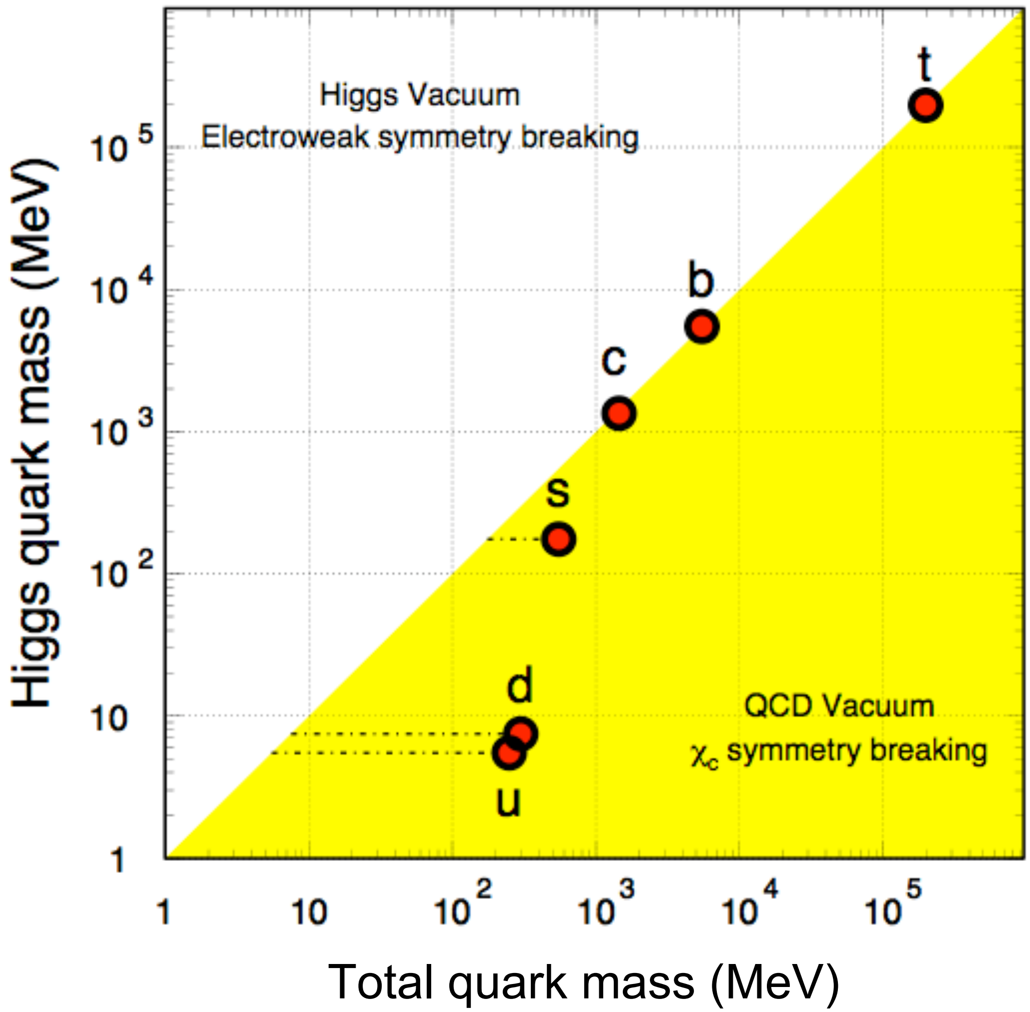
3) Gluons and quarks, or partons, typically exist in a color singlet state: confinement.

Hard QCD Probes



$$d\sigma_{AB\rightarrow hard}(b) = T_{AB}(b)\cdot d\sigma_{pp\rightarrow hard} \qquad T_{AB}(b) \propto N_{bin}(b)$$

Quark Masses



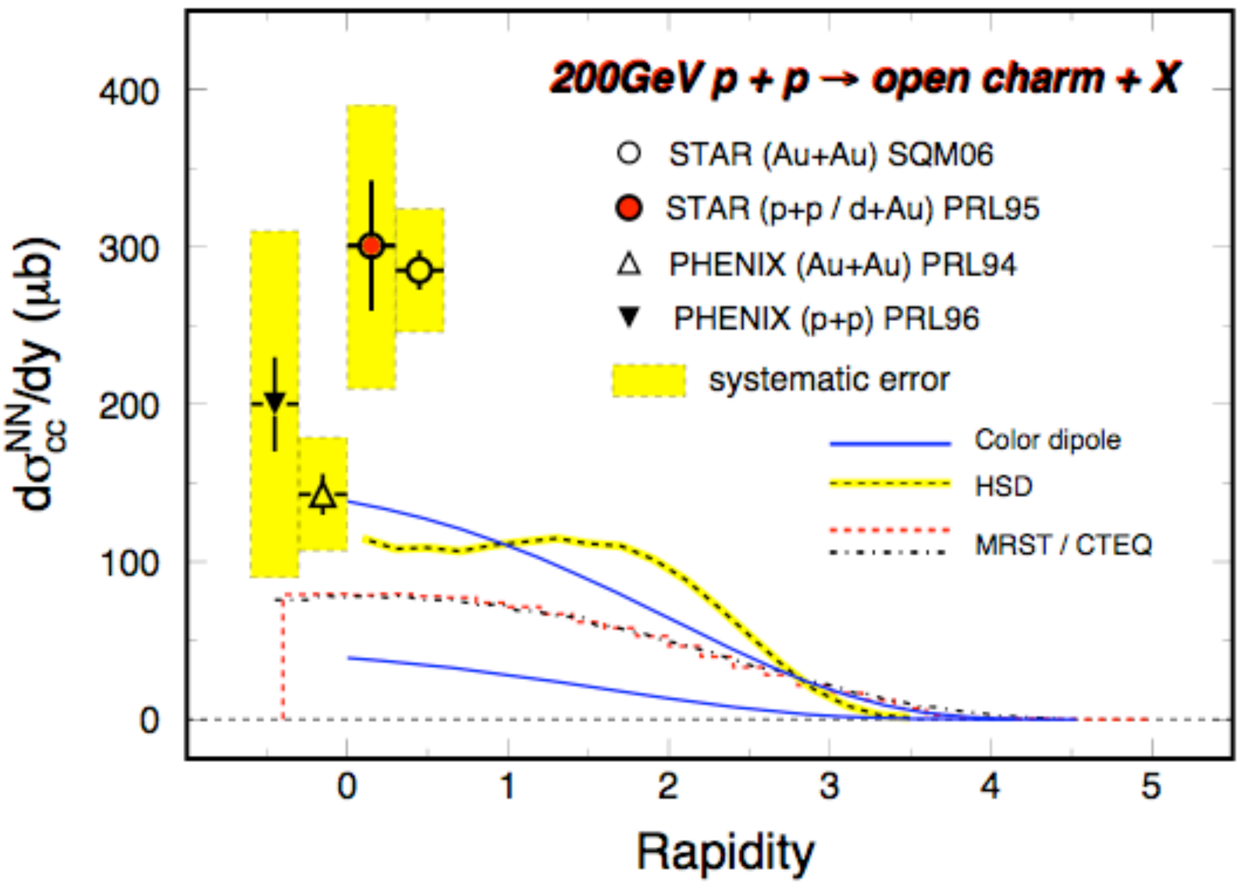
1) Higgs mass: electro-weak symmetry breaking. (current quark mass)
2) QCD mass: Chiral symmetry breaking. (constituent quark mass)

⇨ Strong interactions do not affect heavy-quark masses.

⇨ Important tool for studying properties of the hot/dense medium at RHIC.

⇨ Test pQCD predictions at RHIC.

Charm Cross Section Results



mid-y data

STAR:

$e^{\pm}$, $\mu^{\pm}$, D, e-K

PHENIX:

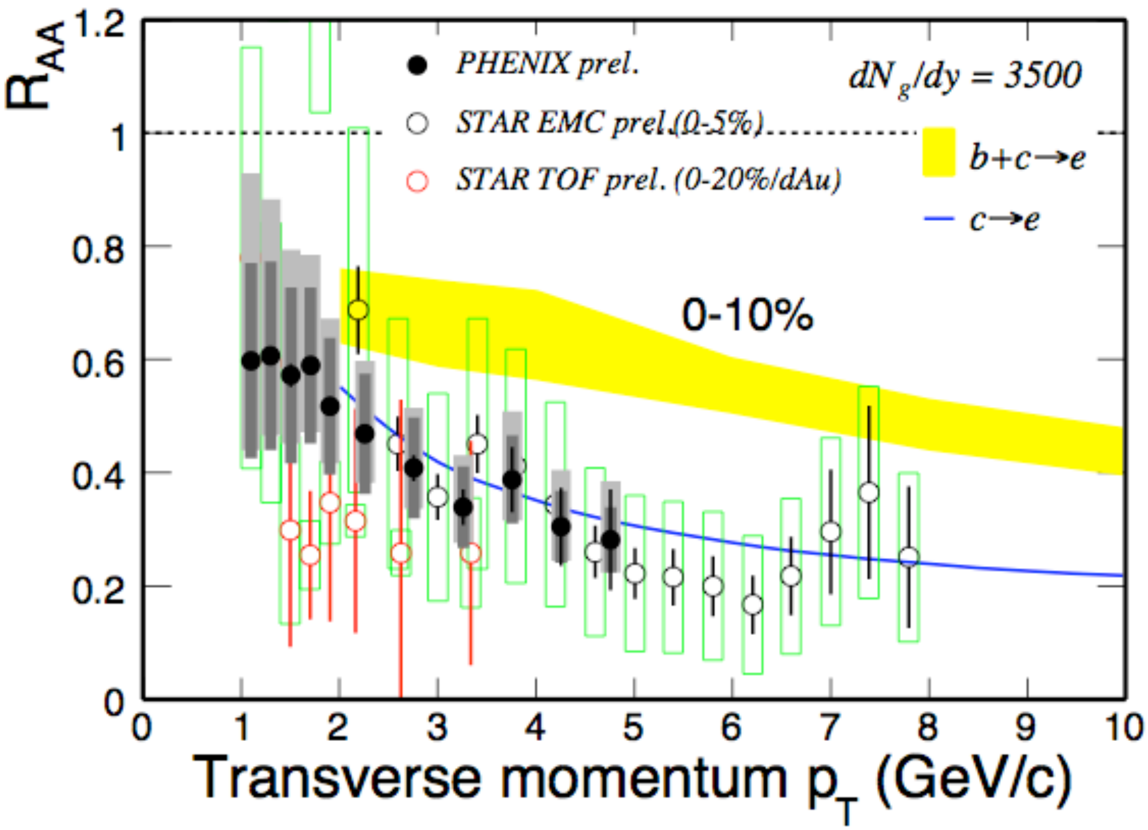
$e^{\pm}$

First set of measurements:

1) Number of binary collision scaling ⇨ initial production
2) pQCD models under-predict charm cross sections
3) Systematic errors are large. Precision data are needed.

Heavy Flavor Energy Loss

M. Djordjevic, et. al. nucl-th/0507019



1) Non-photonic electrons decayed from - charm and beauty hadrons

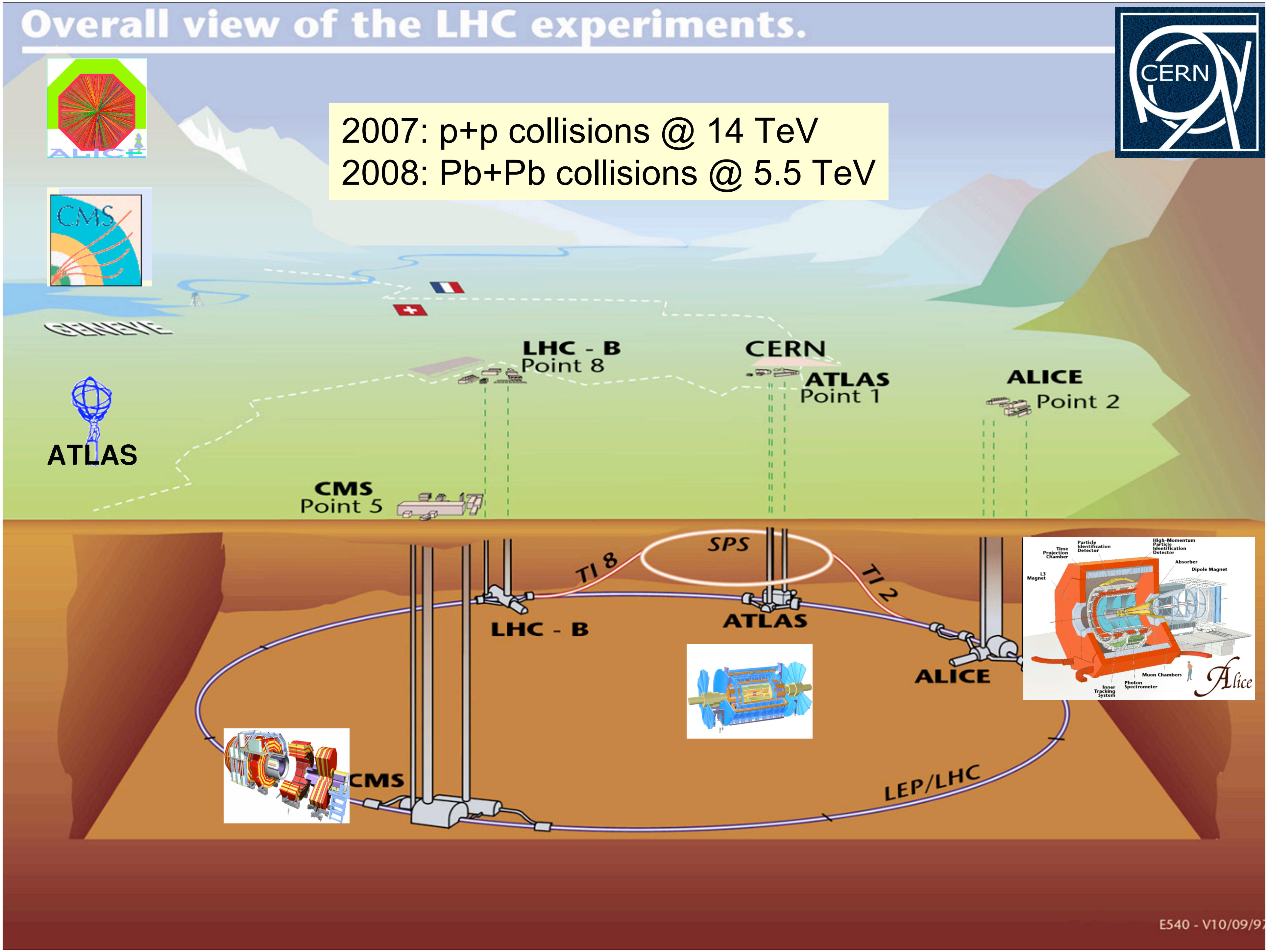
2) At $p_T \geq 6$ GeV/c,

R_{AA}(n.e.) ~ $R_{AA}(h^{\pm})$

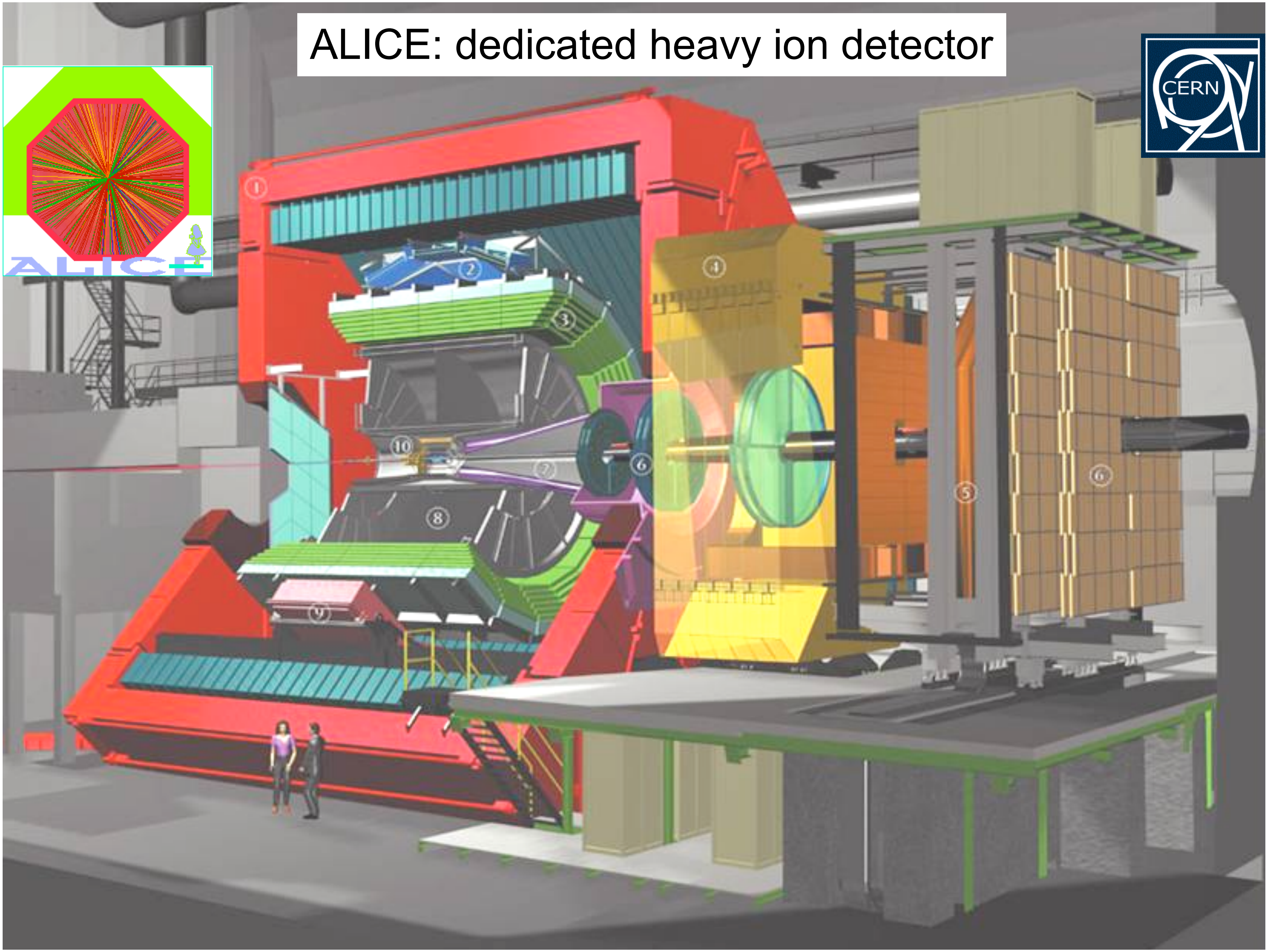
contradicts to naïve pQCD predictions

Surprising results -

- challenge our understanding of the energy loss mechanism
- force us to RE-think about the collision energy loss
- requires isolation of c-hadrons contributions from b-hadrons


Overall view of the LHC experiments.
2007: p+p collisions @ 14 TeV
2008: Pb+Pb collisions @ 5.5 TeV
CERN
CMS
ATLAS
GENEVE
LHC - B
Point 8
CERN
ATLAS
Point 1
ALICE
Point 2
CMS
Point 5
SPS
TI 8
TI 2
LHC - B
ATLAS
ALICE
CMS
LEP/LHC
Time Projection Chamber
Particle Identification Detector
High-Momentum Particle Identification Detector
L3 Magnet
Absorber
Dipole Magnet
Muon Chambers
Photon Spectrometer
Inner Tracking System
Alice
E540 - V10/09/97

ALICE: dedicated heavy ion detector



Outlook

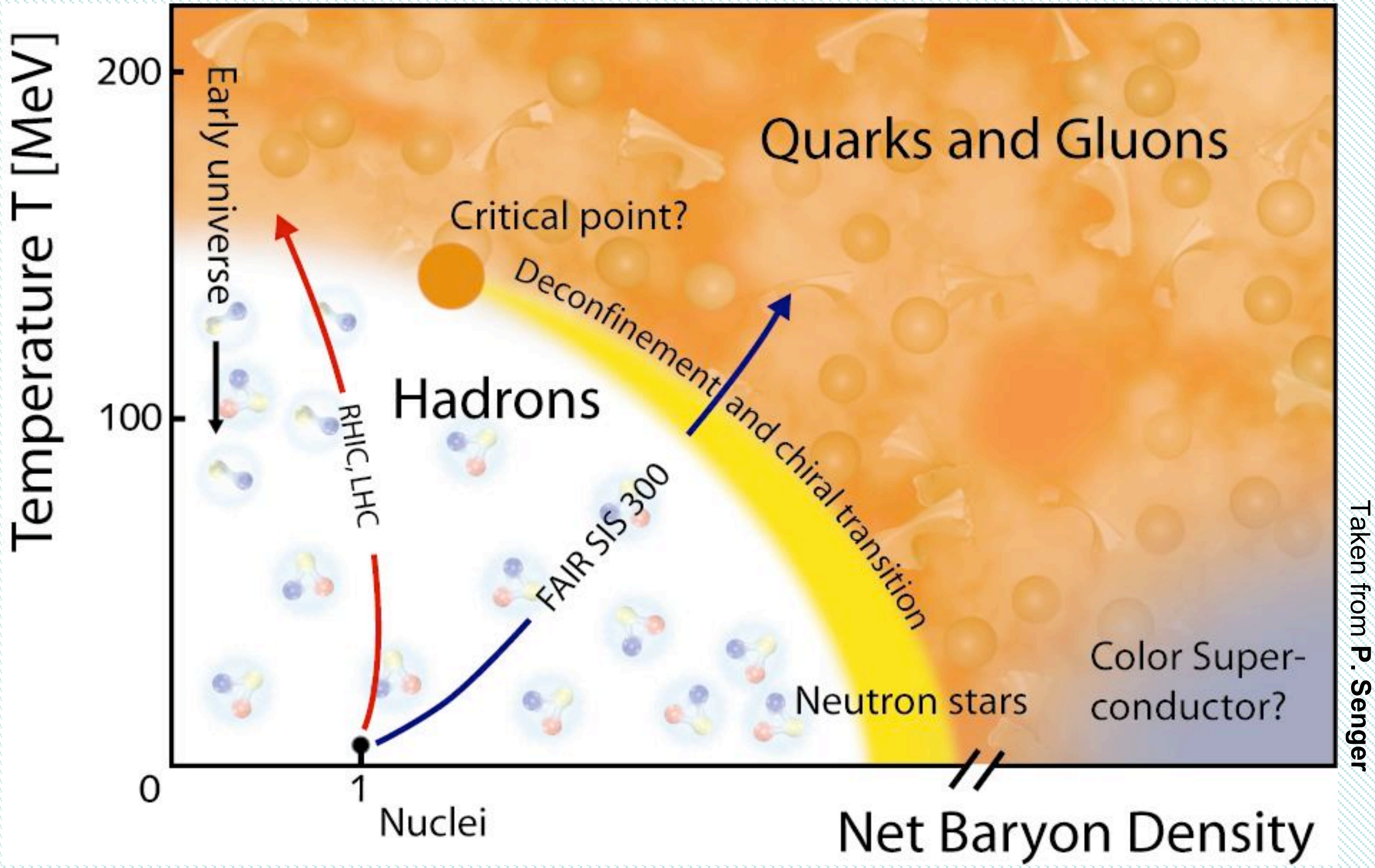
RHIC upgrades and new LHC programs:
(now-2012) (2008)

- high p_T c-hadron spectra
  ⇨ pQCD properties in hot/dense medium

- precise data on total cross section for c- and b-hadrons
- c-hadron correlation functions and flow
  ⇨ heavy flavor collectivity and light flavor **thermalization**

- more surprises: …

⇨ New era for understanding the QCD medium properties at both RHIC and LHC is coming.

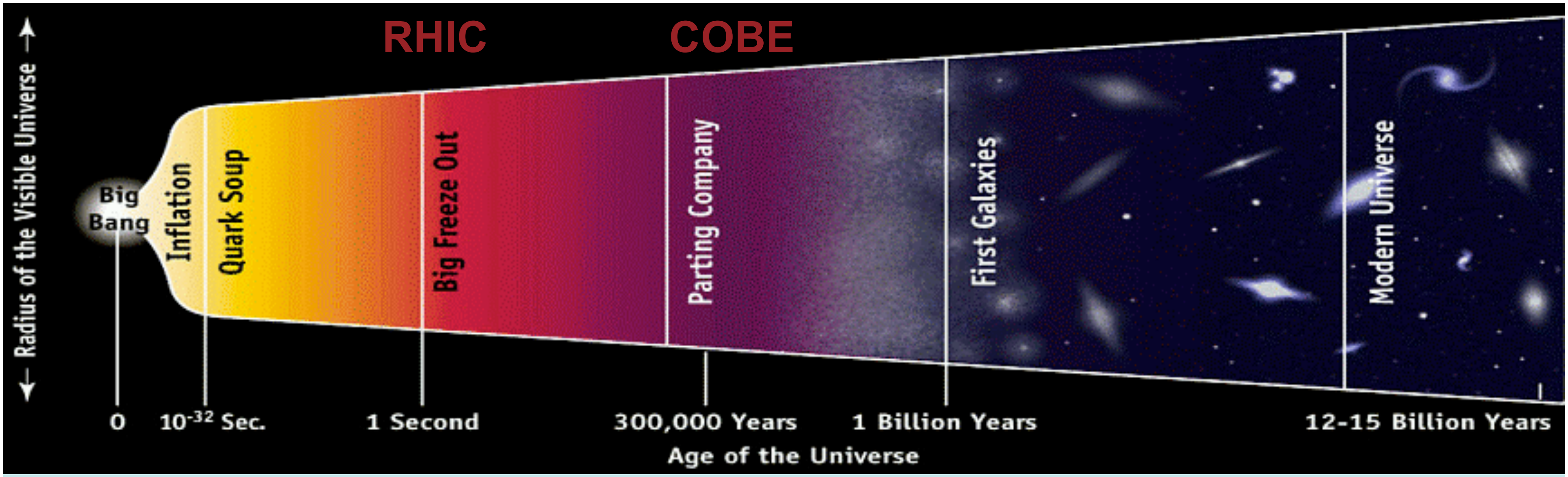


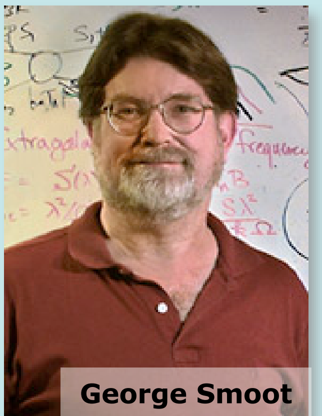
1) RHIC heavy-flavor program / LHC:

- Study ***medium properties***
- pQCD in hot and dense medium

2) RHIC energy scan / GSI program:

- Search for ***phase boundary***.
- Chiral symmetry restoration

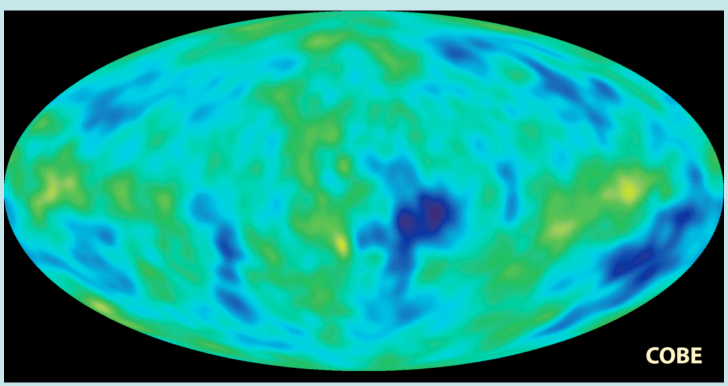




The Nobel Prize in Physics 2006

http://www.lbl.gov/Publications/Nobel/

"for their discovery of the blackbody form and anisotropy of the cosmic microwave background radiation"



COBE: Discovery `baby photo' of the universe

RHIC: Life history of the universe